# Design Knowledge Capture and Reuse in An Integrated and Collaborative Working Environment

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# Declaration

Whilst registered as a candidate for the above degree, I have not been registered for any other research award. The results and conclusions embodied in this thesis are the work of the named candidate and have not been submitted for any other academic award. This dissertation contains 44502 words.

Hao Qin

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# Abstract

Capturing engineering designers' knowledge and experience on the design of an artefact is important as this knowledge can explain why the artefact has been designed as it is, how key decisions have been made and what important issues have been considered. This tacit design knowledge enables designers to make informed decisions and improve efficiency in similar projects in the future. However, the capture and reuse of this kind of knowledge reminds to be great challenge, as it often exists in designers' brains and is difficult to codify. Previous research is predominantly focused on the explicit knowledge of design objects that can be codified rather than the underlying tacit knowledge which explains the problem-solving strategies and decision-making processes. Additionally, engineering design is increasingly conducted in a collaborative working environment enable by the stat-of-the-art information technologies. This trend has highly influenced the ways of knowledge capture and reuse, while is not well addressed by existing research. To fill these gaps, this research aims to explore new systematic methods and knowledge models for the capture and reuse of design knowledge as well as for the development of the next-generation knowledge management systems for engineering design. The development and application of these systematic methods and knowledge models requires a good understanding of the new requirements of knowledge management for engineering design, involving interdisciplinary research work across engineering and computing science. Thus, a comprehensive methodology is employed in this research, which consists of three parts. Firstly, a requirement analysis is undertaken through a literature review and a survey study to identify designers' information needs and information-seeking behaviours within the new context. Secondly, the characteristics of engineering design knowledge are analysed, and on this basis a knowledge framework and a knowledge representation model are developed to support knowledge categorisation and representation. Thirdly, a methodology for applying these methods is analysed in order to design and develop a prototype system for implementation. Through the evaluation of both the proposed methods and system in a number of engineering design projects, the models have been proved to be capable and efficient in capturing design knowledge for better reuse, while the system not only proves the feasibility of the proposed methods but also provides the prototype of the next-generation collaborative knowledge management system.

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# Nomenclature

| | |
|---|---|
| **AJAX** | Asynchronous JavaScript and XML |
| **API** | Application programming interface |
| **CAD** | Computer Aided Design |
| **CAM** | Computer Aided Manufacture |
| **CFRL** | Causal Functional Representation Language |
| **CSS** | Cascading Style Sheets |
| **ERP** | Enterprise Resource Planning |
| **HTML** | Hyper Text Markup Language |
| **ICT** | Information Communication Technology |
| **FBS** | Function Behaviour Structure |
| **FCBS** | Function Cell Behaviour Structure |
| **FEA** | Finite Element Analysis |
| **FR** | Functional Representation |
| **IT** | Information Technology |
| **KM** | Knowledge Management |
| **MCACD** | Computer-Aided Conceptual Design of Mechanisms |
| **P3** | Product Process Project |
| **PDM** | Product Data Management |
| **PDS** | Product Design Specification |

| | |
|---|---|
| **PHP** | Professional Hypertext Preprocessor |
| **PLM** | Product Lifecycle Management |
| **RFBS** | Requirement Function Behaviour Structure |
| **RFBSE** | Requirement Function Behaviour Structure Evolution |
| **SBF** | Structure Behaviour Function |
| **SysML** | System Modelling Language |
| **SQL** | Structured Query Language |
| **TSBF** | Topology Structure Behaviour Function |

# Chapter 1

# Introduction

## 1.1 Background and Motivation

Knowledge management has become a significant topic within the highly competitive production sectors in which the primary issues of product development are related to time, cost and quality. Nowadays, most new products are not invented from none, but improved and adapted from previous designs. In this case, reuse of useful knowledge and experience accumulated in previous designs can greatly improve design efficiency and as such allow more effort to be made in the area for product innovation. Thus, knowledge management helps improve the design process in terms of time and cost, and as consequence results in better quality. However, reusing previous design is not an easy task as a huge amount of data is usually generated throughout an engineering design project. Therefore, identification of which types of data are useful and how to place these data in clear contexts have become the key challenges for reusing previous designs. Previous research on knowledge management for engineering design has indicated that in order to reuse previous design effectively and efficiently, the knowledge behind the scene plays an important role (Bracewell, Wallace, Moss, &

Knott, 2009; McMahon, Lowe, & Culley, 2004). Design knowledge can explain important questions when approaching a design problem such as why a previous product has been designed in a certain way, why a specific structure has been used for a component in the product, how the decisions made have been justified, etc. By explaining the underlying principles and problem solving strategies, design knowledge helps design engineers to reuse the useful parts of previous designs more confidently and efficiently.

Due to the importance, diversity and complexity of design knowledge, researchers have spent a large amount of effort on the topic of knowledge management for engineering design, which has lasted more than three decades. This has resulted in a range of knowledge models as well as some computer support tools developed to support and undertake knowledge management tasks. However, a lot more effort is still needed as the way of doing design as well as the working environment have changed whilst the amount of information generated during the design process has dramatically increased. There are a number of reasons for these changes. Firstly, nowadays engineers tend to do most of their work on computers and in a distributed working environment where they need to access and share information and knowledge on Web. The cognitive process of problem solving during engineering design is extremely complicated, and engineers often need to consult their experienced colleagues to obtain the underlying knowledge for fully understanding the problem solving strategies (Ahmed, Wallace, & Blessing, 2003). With the support of advanced Web technologies, this inter-personal consultation can be done in a virtual and distributed environment. Secondly, with the rapid development of the Internet and its related technologies particularly in the past ten years, the ways of learning, recording and sharing information and knowledge have changed significantly. The information people used to spend hours or even days to find and access in the past may only require a few minutes nowadays with the help of information systems and resources on the Internet. People are now doing more work in a virtual and collaborative environment. Thirdly, the power of computers has greatly improved which is ascribed to the continuous upgrading of hardware and software. As such, Artificial Intelligent and data processing technologies make it more likely that information and knowledge can be recommended and supplied to users according to their contexts of working. In response to these changes, the way of undertaking knowledge management in engineering design should also be reconsidered.

With this background, the main motivation of this research is to explore a new way of managing the useful knowledge and experience of engineers in approaching design problems for its effective and efficient reuse. Traditionally, knowledge management is mainly undertaken by storing and organising structured design data which can be managed and retrieved through Product Data Management (PDM) systems. When engineers want to reuse previous designs, they can search for the data they need from these systems. However, in most cases what they can obtain are merely raw data, e.g. engineering drawings, table of materials, 3D CAD models, etc. which can hardly explain the underlying design knowledge on their own for effective reuse. In this case, it tends to be difficult for design engineers to figure out why particular solutions were used for previous artefacts or components and in what context. These kinds of design knowledge are significant for the reuse of a previous design, while they hardly to be captured and stored in the current knowledge management system. The design knowledge is behind the scene and always exists in engineers' brains, which in some cases is known as experience. This kind of tacit knowledge is an important part of a company's intellectual property, while is highly difficult to articulate and capture (Bracewell et al., 2009). The main reason why existing systems cannot capture this kind of design knowledge is that they do not have a specific method or a knowledge model to guide this task. To fill this gap, this research has proposed a knowledge representation model and developed a prototypical Web-based knowledge management system for undertaking knowledge capture and reuse within a collaborative working environment. It emphasises a knowledge-centred solution rather than data-centred solution for knowledge management, aiming to provide effective methods and solutions for the next-generation of knowledge management systems by analysing new ways of acquiring design knowledge, developing new models of representing integrated knowledge and utilising newly developed information technologies.

## 1.2 Objectives and Thesis Outline

This thesis aims to explore a systematic method to capture engineers' design knowledge and experience during an engineering design project within a collaborative working environment, in order to reuse previous design effectively and efficiently. The main objectives and tasks of this research include three parts: (1) analysis of requirement on knowledge capture and reuse, (2) development of theoretical methods and models, and (3) exploration of ways for the implementation of a knowledge management system embodying the methods and models. Specifically, the requirement analysis part is undertaken through a literature review and a survey study to identify the information needs and information-seeking behaviours of a new generation of engineers during the design process as well as to find out what kinds of guidance they require to access useful information and fulfil their information needs effectively and efficiently. Then, the theoretical methods are proposed to capture, organise and reuse design information and knowledge, including a Product-Process-Project (P3) framework and a

Requirement-Function-Behaviour-Structure-Evolution (RFBSE) knowledge representation model. Based on the results and findings from the requirement analysis and the models proposed, a Web-based integrated knowledge management system has been designed and developed for undertaking the knowledge capture and reuse tasks within a collaborative working environment. Figure 1.1 shows the structure of this thesis and highlight the main tasks of this research which has been mentioned above and are described in details in the following chapters.

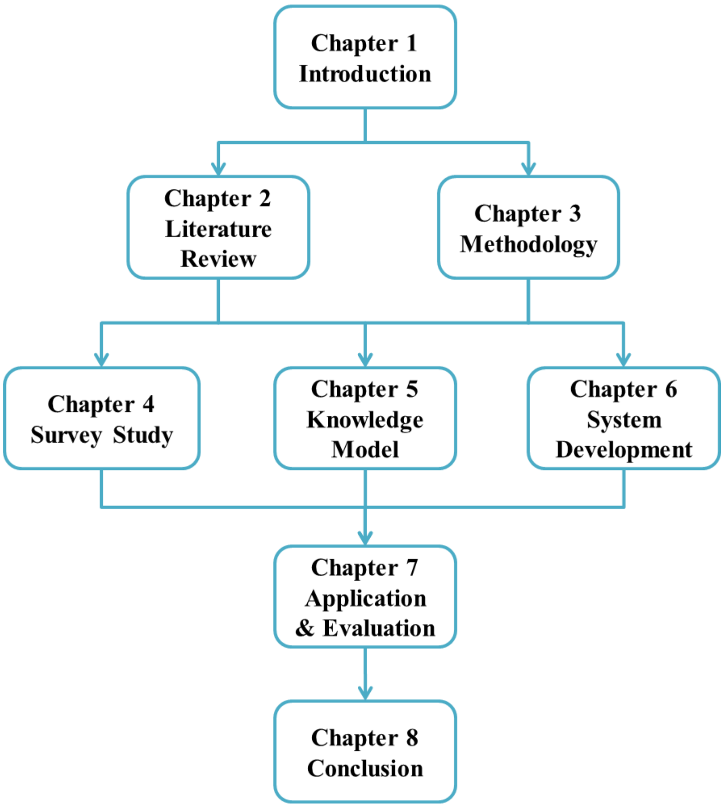


Figure 1.1. Structure of the thesis

In order to understand the research area related to this work, a literature review is conducted in Chapter 2. The review focuses on five aspects: (1) the overview and development of knowledge management in engineering design research field; (2) previous studies on investigating engineers' information needs and information-seeking behaviours and their main conclusions; (3) previous works on knowledge representation and reuse with relevant models proposed; (4) the computer support tools for knowledge management in engineering design and (5) the application of knowledge management in a collaborative working environment. The results of this literature review are used to support discussions in other chapters.

Before detailing the main activities and findings of this research, the methodology of the research is discussed in Chapter 3. It firstly identifies and discusses the special characteristics of engineering design research, and then explains the core ideas of design research and the detailed procedures of conducting this kind of research. Specifically, the methodology of this research includes undertaking a survey study to understand designers' particular information needs and information-seeking behaviours in a collaborative working environment support by new information technologies, proposing and devising a knowledge representation model for addressing the new needs, and developing and evaluating a knowledge management system.

In order to make comparison with the results obtained in the literature review and get some new ideas about the way of capturing and reusing knowledge by a new generation of engineers, a survey study is undertaken in Chapter 4. This survey study tries to compare previous findings on engineers' information needs and their information-seeking behaviours with the current situation in which designers work in a virtual and collaborative environment supported by newly-developed information technologies. In this case, a group of engineers is chosen as the research subjects for the survey study. The results of the survey study support the tasks detailed in Chapter 5 and Chapter 6.

Through an analysis both the results obtained from the survey study and the previous research on knowledge representation and reuse, a knowledge framework and a knowledge representation model are proposed in Chapter 5. The former one is a

Product-Process-Project (P3) framework which is used in building a systematic structure for classifying and organising design knowledge. Also this P3 framework provides ideas for the system architecture of a Web-based knowledge management system to be designed and developed in Chapter 6. A Requirement-Function-Behaviour-Structure-Evolution (RFBSE) knowledge representation model is proposed to provide guidance on how to describe integrated design knowledge using a structured representation during the design process. This RFBSE model together with its application methods are used to provide guidance for the development of the prototype system introduced in Chapter 6.

Based on the P3 framework and the RFBSE model, a Web-based knowledge management system is designed and developed in Chapter 6, together with a methodology on how to undertake knowledge capture tasks using the guidance of the proposed models and their implementations within the system. The system architecture is designed based on the P3 framework and the RFBSE model, considering how to capture, classify and organise design information and knowledge through an engineering design project. The core functionality of the system is to capture design knowledge, supported by the RFBSE model as a model-based solution for knowledge capture and representation. As the system aims to perform within a collaborative working environment, its development relies on several Web programming languages and technologies. The design and development of the system using these technologies will also be described in this chapter, including the user interface, the main applications components and the repository.

The practical applications of both the RFBSE model and the Web-based knowledge management system are discussed in Chapter 7. For the RFBSE model, a complete engineering design project has been chosen to explain how to apply the model to support knowledge capture throughout the design process. Also, evaluations have been done on the model by comparing it with several previous proposed models. For the Web-based knowledge management system, three different engineering project examples are used to explain the application of the system in various areas, i.e. design solution generation, design improvement, and maintenance.

The main conclusions of this research are drawn in Chapter 8. Firstly, a review of the thesis is given. Then, the main conclusions and findings of this research will be summarised. Finally, some discussions on potential future work are given.

# Chapter 2

# Knowledge Management in Engineering Design: A Literature Review

## 2.1 Overview

Engineering design is a systematic process which involves requirement analysis, design specification, conceptual design, embodiment design, detailed design, and then production (Pahl, Beitz, Feldhusen, & Grote, 2007). A more information-oriented view of this design process is the multi-step process through which design ideas are transformed into the information required to create a product (Hales & Gooch, 2004). In both case, managing the information and knowledge generated within the engineering design process is essential, as designers shall have fast access to the relevant information required to carry out their jobs (Quintana-Amate, Bermell-Garcia, & Tiwari, 2015). The information and knowledge generated may also be reused in other projects in the future. Nowadays, there is enormous pressure on the designer in terms of demands for a faster turnaround time, lower margin for error, efficiency in managing resources not only for the product but also for the design process, a greater need to collaborate in multidisciplinary teams (Chandrasegaran et al., 2013). This is further complicated by the virtual explosion in the volume of data that needs to be processed in order to make better-informed decision. Thus, the process of converting data to information, and subsequently to knowledge, and to represent, store, and use that knowledge has become increasingly crucial (Chandrasegaran et al., 2013). In this sense, research on knowledge management for engineering design should be undertaken so as to improve decision-making in the design process.

It is widely acknowledged that the effective managing knowledge in engineering design is significant and can help improve design efficiency (McMahon, Lowe, & Culley, 2004). Knowledge management is defined as 'the explicit and systematic management of vital knowledge and its associated process of creation, organisation, diffusion, use and exploitation' (Skyrme, 2001). There are mainly two knowledge management approaches, namely personalization that emphasises human resources and communication, and codification that emphasises the collection and organization of knowledge (McMahon et al., 2004). Knowledge management for engineering design activities include initiation, generation, modelling, repository, distribution and transfer, use, and retrospect (Gunasekaran & Ngai, 2007), and concentrate on systematic creation, leverage, sharing and reuse of knowledge resources in a company (Awad & Ghaziri, 2007). McElroy (2003) identified two generations of knowledge management methods. The first generation adopted a limited concept of a knowledge lifecycle model and focused on managing information in the form of tangible documents, while the second generation tended to encompass a range of organizational, managerial and technologically orientated approaches to promote the exploitation of an organization's intellectual assets.

Knowledge management is regarded as one of the key enabling technologies for distributed engineering enterprises (McMahon et al., 2004). For many organisations, information is a prerequisite for the production and delivery of their products or services and it is critical for the creation of the next generation of product or service (Hicks, Culley, & McMahon, 2006). Undertaking knowledge management, therefore, is critical in improving the efficiency of production or delivering service. Thus, knowledge management is widely accepted to be one of the key mechanisms for improving the organisational performance and operating efficiency of an enterprise (Chaffey & White, 2010; López-Nicolás & Meroño-Cerdán, 2011). Undertaking knowledge management in engineering design is also beneficial for optimising decision-making process, allowing the sharing of information during the different stages in engineering projects. The consequence of an optimised decision-making process in design is the reduction on the number of iterations required to produce successful designs, and the immediate effect to competitiveness is the reduction of design lead time and costs (Quintana-Amate et al., 2015). Moreover, Bermell-Garcia et al. (2012) has demonstrated the benefits of undertaking knowledge management including: (1) making the knowledge from manufacturing experts available to engineering designers facilitates the adoption of manufacturing considerations in the design and; and (2) transferring the knowledge into software which transforms the knowledge into actionable methods and tools that can be exploited to support the design process more efficiently.

## 2.2 Understanding Knowledge Management in Engineering Deign

In order to undertake knowledge management in engineering design effectively and efficiently, identification of the data, information and knowledge generated during the design process as well as their differences is required. Besides, the information needs and information-seeking behaviours of designers should also be studies in order to provide suitable methods and tools to support and guide engineers in capturing design information and knowledge. The previous researches on these aspects are reviewed in the following sections.

### 2.2.1 Data, information and knowledge

There are several definitions for data, information and knowledge depending on the different sectors in which they are used. In engineering design, these terms are concerned with the product design, manufacture and other product life cycle issues. Data are raw symbols which have no engineering meanings individually, e.g. a number, a formula, a material, etc. When data are used in specific situations, they become information, e.g. a formula that is used to calculate the power of an engine. Knowledge is valuable intellectual asset generally possessed by humans, which is the key of understanding of how to use data and information as well as why to use them in a particular way. For example, it can be used to explain how to improve a part design based on the existing data and information or why a particular material is used for a specific component. (Chen et al., 2009; Hicks, Culley, Allen, & Mullineux, 2002; Stafford, 2006)

Data are available to an organization in the form of observations, computational results and factual quantities. Interpretation, abstraction or association of this data leads to the generation of information. Finally, knowledge is obtained by experiencing and learning from this information and putting it into action (Owen & Horváth, 2002). Information is data together with a specific context, and it answers the ‘who’, ‘what’, ‘where’, and ‘when’ (Bellinger, Castro, & Mills, 2004). Information is comprised of a number of data parts and their descriptions, and knowledge is the ability of the individual to understand of data parts and their descriptions, manner in which why handle, apply and use it in a given situation (Court, 1995). In engineering design, the information has two categories, namely formal and informal information. The former includes structured textual, structured pictorial, and explanative verbal information, while the latter consists of unstructured textual information, unstructured pictorial information, conversational verbal information, memory, and expressions (Hicks et al., 2002).

Knowledge is not directly available but is obtained by interpretation of information deduced from analysis of data. Knowledge is information that is structured and organised as a result of cognitive processing and validation, and it may be explicit (e.g. written guidelines) or implicit (experience, intuition) (Cooper, 2010). Knowledge can also be considered as information in context. This context depends on a number of variables, i.e. the product being designed, the organisation, the design philosophy followed, the particular stage of design at which the knowledge is being used, and most important of all, the mind of designer (Chandrasegaran et al., 2013). In the management sector, knowledge is defined as information within people’s minds (Davenport, De Long, & Beers, 1998). In the context of engineering design, knowledge is an understanding of some pieces of information given to designers, including their contents, origins and their applicability (Sunnersjö, 2010). Knowledge can be described as experience, concepts, values, beliefs and ways of working that can be shared and communicated (Sainter, Oldham, Larkin, Murton, & Brimble, 2000). It is argued that design knowledge should include not only the rules that the designer should adhere to, but also the background knowledge that makes the design rules possible to review and understand (Sunnersjö, 2010). Besides, while it is important to understand and define what knowledge is, it is equally significant to understand the definition of knowledge depends upon the context (Chandrasegaran et al., 2013).

The clarification of the differences between data, information, and knowledge helps to capture and reuse these resources effectively and efficiently. Both information and knowledge contribute significantly to the transformation and creation of the designed artefact, they provide for the basis of all possible decisions, and decision processes (Hicks et al., 2002). In the industry, upward of 80% of design is adaptive or variant (Pahl et al., 2007), resulting in a process that is particularly reliant on information and knowledge. An improved process and better final design can be achieved through the efficient and effective utilisation of information and knowledge resources for engineering design. In order to best utilise this information and knowledge it is necessary to provide effective means for its identification, capture, storage and reuse (Hicks et al., 2002).

### 2.2.2 Information needs

The research in understanding designers' information needs has been lasted for decades. During an engineering design project, designers require a great amount of information and use it in a variety of ways, including task initiating, focus forming, idea assuming, idea rejecting, idea confirming, idea finalizing, idea sharing, approval granting, and design generating (Cheuk & Dervin, 1999). The design information and knowledge can be characterised in terms of its relevance to the product, process, and resources (Marsh, 1997), whilst it can also be considered to be related to detailed issues such as cost, environment, time and quality (Cantamessa, 1997). Among this great quantity of information, finding which kinds of information are useful to designers is one of the most significant issues. According to Baya (1996), the information needs of designers can be described in terms of alternatives, construction, location, operation, performance, rationale, relation and requirement. Similar research identifies engineers' knowledge and information needs, throughout the whole product life cycle, in requirements, design solutions, option & choices, change/modifications, manufacturing information, service, performance, and maintenance information (Heisig, Caldwell, Grebici, & Clarkson, 2010). However, designers might not know exactly what information they require and also have problems in identifying the appropriate information sources (Hirsh, 2000), and this phenomenon is more evident for novice designers (Ahmed, Wallace, & Blessing, 2003). Identification of what knowledge should be captured, and attempts to identify the knowledge needs of designers have been largely upon characterising the type of knowledge designers require (Ahmed & Wallace, 2004). An important issue in effectively fulfilling designers' knowledge needs is to understand the contents and usage of the information by them throughout the design process from particular sources such as logbooks (McAlpine, Hicks, Huet, & Culley, 2006; Wasiak et al., 2011; Wild, McMahon, Darlington, Liu, & Culley, 2010).

### 2.2.3 Information-seeking behaviours

The information-seeking behaviours of designers have been studied in order to explore effective ways of fulfilling their information needs, and this research has been lasted for nearly half a century. A significant conclusion by Chakrabarti et al. (1983) is that ease of use and availability are the two most important factors determining the information sources selected by engineers. Similarly, Pinelli (1991) showed that accessibility is the most important determinant of the sources to be used by the engineers working in industrial research and development. As to the ways of seeking information, several studies have shown repeatedly that engineers rely most heavily on internal sources for information, mainly through interpersonal communication with colleagues (Lechie & Pettigrew, 1996). Shuchman (1982) found that conversations with colleagues, consulting supervisors, and reading in-house technical reports are the most important internal sources, while the study of Chakrabarti et al. (1983) revealed that work groups were the most frequently used information source. Different from these findings, Court (1997) asserted that engineering designers depend mainly on their personal memories while carrying out design activities. Also, a number of studies found that the cost associated with using an information source is the most important determinant of its use (Hertzum & Pejtersen, 2000). For the time that engineers spent on information-seeking behaviours, several studies provide evidence that engineers spend 40 to 60% of their time communicating in order to get information they require (King, Casto, & Jones, 1997). However, more recent research by (Allard, Levine, & Tenopir, 2009) shows that engineers spend about a quarter of their day engaged in some types of information-seeking events, which is lower than the percentage identified in the previous research. The explanation for this may be rooted in the significant change in IT that now makes information more accessible to designers. For instance, information retrieval technology has greatly improved, which makes search of information more effective and efficient, and encourages engineers to use the Internet as a primary source of information. Furthermore, previous research has established that engineers aim at minimizing effort when they seeking information (Fidel & Green, 2004), indicating that computer tools which can provide support to the engineers' information-seeking behaviours are preferred.

## 2.3 Knowledge Representation and Reuse

Based on the requirements for knowledge management in engineering design, methods can be proposed and developed to support this process. These methods can be divided into two levels, namely the abstract level and the application level. The abstract level is to use information and knowledge models to capture, represent and organise information and knowledge, while the application level is to develop computer support tools for the practical implementation of the methods developed. The abstract level guides the application level, and it should not only provides the fundamental part for the computer support tools but can also guide the users. The following sections will explain about knowledge representation and review the existing models from previous research that can be used for knowledge representation.

### 2.3.1 Knowledge representation

Knowledge representation can be described as a multidisciplinary subject that combines techniques from logic, ontology, and computation. The origins of knowledge representation lie in research in artificial intelligence, but its influence has extended to many fields, including the design process (Sowa, 2000). The knowledge generated within engineering design can be classified into formal knowledge and tacit knowledge. Specifically formal knowledge is embedded in product documents, repositories, product function and structure description, solving routines, technical and management systems, computer algorithms, expert knowledge systems, etc. (Owen & Horváth, 2002). At the same time, tacit knowledge tied to experiences, intuition, unarticulated models or implicit rules of thumb (Chandrasegaran et al., 2013). It exists as the intellectual property of designers or a particular design team, and is generally gained over a long period of time with learning and experience. Unlike formal knowledge, tacit knowledge is difficult to express, and can only be transferred by the willingness of people to share their experiences (Chandrasegaran et al., 2013).

Also, the knowledge existed in an engineering design project can be divided into product knowledge and process knowledge; Product knowledge includes various pieces of information and knowledge associated with the evolution of a product throughout its lifecycle, which includes requirements, various kinds of relationships between parts and assemblies, geometry, functions, behaviour, various constrains associated with products, and design rationale. The process knowledge can be classified into the knowledge from the design process, the knowledge from the manufacturing process and the knowledge form the business process (Chandrasegaran et al., 2013). Furthermore, knowledge can be classified into compiled knowledge and dynamic knowledge. Compiled knowledge is essentially the knowledge gained from experience that can be compiled into rules, plans or scripts, cases of previously solved problems, etc., while dynamic knowledge encodes the knowledge that can be used to generate additional knowledge structures (Chandrasegaran et al., 2013). There are two levels of dynamic knowledge, namely qualitative and quantitative knowledge. At the qualitative level, the knowledge may consist of common sense reasoning, approximate theories, causal models of processes, general problem solving knowledge, etc.; quantitative level could include constitutive, compatibility, equilibrium equations (physical laws), numeral techniques, closed form equations, etc. (Sriram, 1997).

Considering how the knowledge generated during engineering design, there are two aspects of knowledge production, namely knowledge processes and knowledge elements (Hicks et al., 2002). Knowledge elements are produced by knowledge processes, which are generated by an individual through the understanding, assimilation and application of information and other knowledge elements. These knowledge processes are generally within-person processes, while the knowledge elements can easily be represented due to the fact that knowledge elements are in fact conveyed as information that can be explicitly defined (Hicks et al., 2002). Thus, the knowledge can be represented are mainly the knowledge elements. However, the ways of presenting the knowledge elements affects significantly how the knowledge elements will be processed within engineers' minds. In this case, the knowledge representation models are proposed and developed to give guidance to structure the knowledge elements in order to allow them better processed by engineers.

### 2.3.2 Models for knowledge representation

The research on developing models for representing design objects and further the design knowledge mainly started in the early 1990s. A typical one is the Function-Behaviour-Structure (FBS) model by Gero (1990), which proposed a knowledge representation schema for design. The FBS model gives a systematic view of the main elements during engineering design and their relationships. At that period, discussing how to describe designs based on its function, behaviours and structure became a popular research topic. Relevant studies include the Functional Representation (FR) model and its subsequent Causal Functional Representation Language (CFRL), Structure-Behaviour-Function (SBF) model for analogical design, and Function-Behaviours-State modelling scheme of functions.

FR represents the functioning of a device in many dimensions, including causal, temporal, and interaction. In the causal dimension a “unit of functioning” is represented as a causally related sequence of device (or component) states. In the temporal dimension, these units obey time constrains, e.g. sequentially or overlap. In the interaction dimension, they interact through feedback or by communicating information. Thus, the FR is rich in the number of primitives it employs to represent many aspects of functional knowledge (Sembugamoorthy & Chandrasekaran, 1986). CFRL focuses on the causal mechanism of a device by representing its functions and expected behaviours. It represents knowledge of the functions that a device is intended to achieve and also of the sequence of causal interactions among its components to achieve the functions. In CFRL, the function of the overall device is firstly described and then the behaviour of each component is described in terms of how it contributes to the functions (Iwasaki, Fikes, Vescovi, & Chandrasekaran, 1993). SBF is developed for analogical reasoning, through which an SBF model of a device captures the engineers’ comprehension of how the device works, that is, how the structure of its design results in its output behaviours (Bhatta & Goel, 1994). The SBF model of a design is a generalisation on Sembugamoorthy and Chandrasekaran’s (1986) functional representation scheme. The Function-Behaviours-State modelling is a knowledge representational schema for functions, which defines a function as an association of human intention and behaviour and represents a design object hierarchically (Umeda & Tomiyama, 1995). It aims to provide a methodology to represent and manipulate functions for constructing CAD systems for functional design. It also tries to formalise design processes with an FBS Modeller and increase reliability of design objects by using functional knowledge.

From 2000 to present, the trend of development on models is from describing design objects to include design process and even product's life cycle issues, representing and reusing the design knowledge generated and shared between designers. The further studies based on the models mentioned above have been undertaken for this aim. The Situated FBS framework (Gero & Kannengiesser, 2004) has extends the FBS framework to consider the dynamic character of the context in which designing takes place. Furthermore, a FBS ontology (Gero & Kannengiesser, 2007) presents how the FBS ontology can be used to represent processes despite its original focus on representing objects. It provides a uniform framework for classifying processes, and includes higher level semantics in their representation. Other studies extended FBS include RFBS (Christophe, Bernard, & Coatanea, 2010) which adds requirement analysis as an important element to the model and tries to combine FBS with System Modelling Language (SysML) for practical implementation, and Cascini, Fantoni, & Montagna (2013) also represents needs and requirements and their relationships with FBS to emphases importance of the requirement factor for engineering design. Besides, Gu et al. (2012) has proposed the Function-Cell-Behaviour-Structure (FCBS) model that uses functional knowledge cells (a function-cell pair) with FBS for better comprehending representation and reuse of design knowledge in conceptual design.

For FR research, Chandrasekaran and Josephson (2000) describe an ontology for representing objects and causal interactions between objects, and use this ontology to investigate a range of meanings of the terms “structure”, “behaviours”, and especially “function” in engineering practice. Moreover, based on the SBF concept, an integrated knowledge representation model, namely the Topology Structure Behaviour Function (TSBF) model is presented by Tian et al. (2006) for the Computer-aided Conceptual Design of Mechanisms (MCACD). This TSBF model adds an additional topology level to allow both qualitative behaviour reasoning and topological reasoning, while it is mainly used for the conceptual design of mechanisms. Besides, Goel et al. (2009) views SBF as a programming language and uses it to capture the expressive power of the earlier programmes and provides a basis for interactive construction of SBF models. They specified the abstract syntax and static semantics of SBF language and used SFB models of engineering systems in several computer programmes for automated design and problem solving, rather than focusing on understanding and explaining the complex engineering design objects and processes.

## 2.4 Computer Support Tools for Knowledge Management

### 2.4.1 Requirements and focuses

The use of computational support tools in engineering design enables the capture of knowledge generated at each design stage and the representation of this knowledge to provide decision support for engineering designers (Chandrasegaran et al., 2013). There are a number of support tools for the later stages of design, especially the detailed design stage, while there are much fewer support tools in the earlier stages of the design process such as conceptual design. This reduces the efficiency of designers in manipulating, organising, representing, and using design data (Meniru, Rivard, &

Bédard, 2003). The lack of support during the conceptualisation stage limits the potential of design space exploration as designers are limited by past knowledge, experience and constrains on time and resources (Chandrasegaran et al., 2013). There is an increasing need to make computer support tools more designer-centric, which requires an understanding of the cognitive working process of designers so that the transformation from thought to representation could be made and the generated knowledge can be effectively captured (Ullman, 2002). For the knowledge representation techniques of the support tools, they range from computer-centric techniques which ensure the computational implementation is carried out efficiently, to human-centric techniques which aid the creativity of designers (Chandrasegaran et al., 2013). The evolution of support tools for engineering design is supported by collaboration, artificial intelligence and developments in information technology (Wang et al., 2002). The work in 1980s tried to integrate codified design knowledge from different systems (Chalfan, 1986). A lot of work in 1990s focused on parametric modelling using CAD systems and automatic uncoupling and storage of geometric constrains (Roller, 1991). Geometric modellers, sketchers and constraint solvers became the key components of a parametric computer modelling system at that period of time (Anderl & Mendgen, 1996). These tools mainly focus on the structure of an artefact rather than capturing the knowledge on how the artefact has been designed. After 2000s, a new focus on capturing design rationale by using computer support tools has triggered research on the capture and reuse of tacit design knowledge (Bracewell el al., 2009), which has emphasised the importance of developing computer support tools for capturing design knowledge for reuse.

### 2.4.2 Supporting knowledge management in engineering design

Computer support tools are developed and used to assist capturing and managing the data, information and knowledge within an engineering design project, which can be generally regarded as knowledge management tools. Knowledge management tools were defined as technologies for knowledge generation, codification, and transfer (Ruggles, 1997). The traditional method for implementing knowledge management is to use Product Data Management (PDM) systems to store design data and information in databases, which merely provide access to schematics, Computer-Aided Design (CAD) models, and documentations (Szykman, Sriram, Bochenek, Racz, & Senfaute, 2000). PDM systems manage documents such as reports, CAD data, engineering drawings, and analysis data through the design process. However, there are several shortcomings of these PDM systems, such as the lack of formal product representation in the form of function, behaviour and structure, lack of reuse of design knowledge, lack of impact analysis, etc., (Bilgic & Rock, 1997). Aiming to improve the traditional method, Product Lifecycle Management (PLM) systems have been developed. The concept of PLM appeared in the 1990s as an extension of PDM (Chandrasegaran et al., 2013), and the PLM is defined as the process of managing a company's products from their conception, design, manufacturing, all the way to its use and disposal (Stark, 2005). The purpose of PLM systems is to integrate information on the manufacturing processes (CAM systems) with design data (CAD systems) on the one hand, and information about Enterprise Resource Planning (ERP) processes on the other hand (Brandt et al., 2008). PLM systems have been used by organisations as a means to streamline their processes and to manage their product knowledge. However, these PLM systems lack essential capability for the management and reuse of design knowledge (Gao, Aziz, Maropoulos, & Cheung, 2003; Maropoulos, 2003) and are less suited for the conceptual design stage (Gao et al., 2003; Mesihovic, Malmqvist, & Pikosz, 2004). Moreover, a significant shortcoming of existing PLM systems is that they are lack of adequate information models for product presentation, as these models would be needed to effectively capture, exchange, retrieve, and reuse design knowledge (Szykman, Sriram, & Regli, 2001). Thus, a knowledge management system which can not only fulfil the function of the current PLM systems but also capture the design knowledge for effective reuse will be required.

Knowledge management system method is a systematic process of acquiring, accumulating, and sharing individual knowledge, and uses them to strengthen competiveness (Davenport et al., 1998), and a knowledge management system should be able to explicitly represent the tacit knowledge of designers, and facilitate expansion of the knowledge through the knowledge acquiring-storing-using cycle (Park, 2011). Recent research is focusing on developing a generic representation of product knowledge that includes other kinds of product knowledge beyond structure, function, and behaviour, in order to support a broader level of information exchange and interoperability (Le Duigou, Bernard, Perry, & Delplace, 2008). Product knowledge is represented in terms of requirements, specification, artefacts, structure, functions, behaviours, design rationale, constraints and relationships. Such representation supports multiple levels of abstraction, which provides computational support for early design activities (Szykman, Fenves, Keirouz, & Shooter, 2001). The support tools currently available for capturing design rationale using visualised and structured knowledge representation include the Compendium (Conole, 2008; Shahin, Liang, & Khayyambashi, 2010) and the Design Rationale Editor (DRed) (Bracewell et al., 2009). Also, the DRed tool has been developed and successfully integrated to the Rolls-Royce PLM toolset (Bracewell, Wallace, Moss, & Knott, 2009; Chandrasegaran et al., 2013), which provides a solution for the integrated knowledge management in engineering design.

## 2.5 Collaborative Working Environment

### 2.5.1 Collaborative design

When a product is designed through the collective and joint efforts of many designers, the design process is generally referred as Collaborative Design (may also be called Co-operative Design, Concurrent Design and Interdisciplinary Design) (Wang et al., 2002). According to the functions and roles of users participating in a design activity, a collaborative design activity can be organised in either a horizontal or a hierarchical manner. The horizontal collaboration emphasises on collocating a design team from the same discipline to carry out a complex design task in a synchronous or asynchronous way, while the hierarchical collaboration can establish an effective communication channel between upstream design and downstream manufacturing and enriches principles and methodologies of concurrent engineering to link diversified engineering tools dynamically (Li, Lu, Fuh, & Wong, 2005). The previous research has found the sequential design as brittle and inflexible and often requires numerous interactions, indicating this design scheme makes the design process expensive and time-consuming as well as limiting the number of design alternatives that can be tried out. Besides, as the sequential design is usually practised with downstream information flow, it may cause an inefficient design due to the absence of manufacture-ability checks at the design stage. In this case, collaborative design tries to address these problems concurrently by considering constrains and detecting conflicts early in the conceptual design stage (Wang et al., 2002). The objective of a collaborative design team might include optimising the mechanical function of the product, minimising the production or assembly costs, or ensuring that the product can easily and economically be serviced and maintained (Hartley, 1992).

### 2.5.2 Supporting technologies

To support collaborative design, computer technology must not only augment the capabilities of the individual specialists, but must also enhance the ability of collaborators to interact with each other and with computational resources (Wang et al., 2002). However, engineering design has to address several complex characteristics, e.g. diverse and complex forms of information, interdisciplinary collaboration, heterogeneous software tools etc., and these make interaction difficult to support. The technologies that have been proposed to implement collaborative design include distributed objects, agents and Internet and Web technologies (Wang et al., 2002). The R&D cycle starting from the end of last century is to renovate CAD systems to be distributed and collaborative by using the quickly developed information technology. In a collaborative CAD system, designers and engineers can share their work with globally distributed colleagues via the Internet/Intranet, and work closely with suppliers, manufacturing partners, and customers (Li et al., 2005). In the aspects of enabling technologies, distribution is more fuelled by the development of IT, such as Java, .Net, Web, XML and Web service technologies, and collaboration is more driven by the design and development of effective collaboration mechanisms to facilitate human-human/human-computer relationships (Li et al., 2005).

To achieve collaborative design, the commercial systems such as Product Data Management (PDM) and Product Lifecycle Management (PLM), can offer a structured way of efficiently storing, integrating and managing both data and engineering processes. However, these systems do not consider how to support the collaborative design activities and processes within the knowledge management context, these conventional knowledge management systems can only be used to help in document management, engineering data management or workflow management (Wei, Hu, & Chen, 2002). Also, there is lack of an effective and practical system in capturing, storing, compiling, and retrieving design knowledge and experience in collaborative design (Chen, Chen, & Chu, 2008). In order to capture the useful design knowledge in a collaborative working environment, a knowledge model which can guide both the human users and the computer support tools in capturing, organising and reusing design knowledge is required.

### 2.5.3 Meeting the information and knowledge needs

Collaborative design is a knowledge-intensive process, involving various areas of design knowledge and experience. Whether this design knowledge and experience can be effectively managed, shared and reused is the basis of competent product design (Chen et al., 2008). During the design process, experts from different fields work together and exchange information, expertise, and resources to solve design problems (Penciuc, Durupt, Belkadi, Eynard, & Rowson, 2014). However, the different actors of the collaborative design will not use the same product decomposition and each on builds his/her own viewpoint about the problem to be solved (Noël, Roucoules, & Teissandier, 2005). This complexity requires on or more collaboration processes in order to help designers and decision-makers to perform his/her activity and to converge their heterogeneous points of view to a mutual consensus (Penciuc et al., 2014). Typically, design actors share the same global goal in the project but their individual goals are different according to their activities (Kleiner, Anderl, & Gräb, 2003). While cooperating by negotiation, decision-makers have to interact in order to resolve conflicts through the management of dependencies and contradictions resulting from individual decision (or activities results). This variety of viewpoints and necessity to perform negotiation in collaborative actions, require the development of methods and tools promoting knowledge integration and sharing in the upstream of the product design process. Since the experts collaborate along the whole product lifecycle using different kinds of supports to exchange and build new knowledge, they should use a unique reference for the conflict resolution purpose (Penciuc et al., 2014).

The complexity of modern products poses several challenges to designers, and this increasing complexity necessitates a distributed and heterogeneous collaborative engineering design environment (Sriram, 2002; Wang et al., 2002). Within a collaborative working environment, cross functional teams need a more intensive knowledge exchange process. The knowledge exchanged includes geometry, design rules and constrains, requirements, rationale, etc. Thus, the collaborative engineering requires the support of computational framework (Chandrasegaran et al., 2013). Although the recent developments of ICT (Information and communications technology systems) bring more features for collaborative activities support, the actual available tools fail to track the daily changes of design parameters, constrain or rules and even check data consistency between activities during the design process. Furthermore, information and knowledge of a fine granular level of details are not considered enough (Penciuc et al., 2014). To support the collaborative design activities and the effective knowledge sharing in these activities, an integrated Web-based knowledge management system should be developed. This system enables users to created knowledge records in a collaborative working environment as a design proceeds whilst providing important design knowledge to them according to their context of working.

## 2.6 Summary

The research focuses on the knowledge management in engineering design, trying to explore an effective and efficient way to capture, organise, represent and reuse design knowledge. In order to achieve this goal, several key issues within the research area should be firstly identified. These include the following aspects: (1) what are data, information and knowledge, as well as the differences between them; (2) what are engineers' information needs during the design process, and how can they fulfil the needs; (3) is there any theoretical methods that can be used to support the knowledge management in engineering design, and how can they support the knowledge capturing and reuse; (4) whether the current computer supports tools can assist the design knowledge capture and reuse, and what will be the preferred supporting tool; (5) what kinds of environments the knowledge capture and reuse will be undertaken, and how to effectively provide support by the computer tools. Regarding to these issues, the literature review has been undertaken in these relevant areas and indicates the gaps to be filled by the proposed research.

The literature has shown there is a significant requirement for the knowledge transfer within a company, as the engineers may retire or leave the company and their knowledge and experience is valuable to be retained in the company. Also, this knowledge is essential to guide novice engineers to figure out what kinds of information they really need and how to access and use them. Although some design reports can be used to explain part of the design knowledge, it is not efficient and time consuming to both write and read a long report. Thus, a knowledge management system which can capture and represent knowledge and experience is demanded. However, the current knowledge management systems are mainly focused on managing the data and information, while rarely can deal with the knowledge and experience. The reason why the current systems lack this functionality is because they lack of an information/knowledge model which should be used to guide how to capture and organise design knowledge. Although there are several existing design models which can be used to describe design objects and processes, they are not focused on the knowledge management aspect. Therefore, the task of this research is to propose an information/knowledge model that can be used to guide either the system or the engineers to capture design knowledge and represent it in an organised way for future reuse. Also, a knowledge management system which can capture and manage design knowledge will be designed and developed based on the proposed model for the practical implementation. Within the collaborative working environment, the system should be built in the Web-based computing environment, and should consider how to effectively capture and reuse design information and knowledge through the collaborative design process.

# Chapter 3

# Research Methodology

## 3.1 Methodology of the Research

### 3.1.1 Methodology for design research

The purposes of design research are the formulation and validation of models and theories about the phenomenon of design, as well as the development and validation of knowledge, methods and tools based on these theories to improve the design process (Blessing & Chakrabarti, 2009). A typical characteristic of design research is that it not only aims at understanding the phenomenon of design but also using this understanding to change the current situation. The latter requires more than a model (or theory) of what exists, it also requires a model of what would be desirable and how the existing situation could be changed into desired. Thus, design research includes the research work on improving understanding as well as the development of guidelines and methods, and both directions require different methods and approaches (Blessing & Chakrabarti, 2009).

A research methodology is required to systematically discover and validate knowledge in design research. The characteristics of design and the aims of engineering design in essence involve an attempt to change the present for the better, which requires design research understand how this change can happen and explore how to guide the change. In this sense, the overall aim of engineering design research is to support industry by improving the understanding of engineering design and developing knowledge in the form of guidelines, methods and tools which can improve the chances of producing a successful product (Blessing & Chakrabarti, 2009). Therefore, the methodology of research in engineering design has different characteristics compared to other area of scientific research. Rather than undertaking laboratory experiment to seek new discovery, engineering design research aims to explore new methods to solve engineering and management problems, which means there is no such a single methodology for all kinds of design research. Although there are some relevant general methodologies which can be used as a reference, the methodology should be adjusted depending on the engineering problem to be solved.

The research on knowledge management in engineering design is a particular area within the design research spectrum, and thus the methodology it can use has a similar characteristic to other design research areas mentioned above. It firstly should gain a good understanding of the current situation, and then explores a method for improvement and optimisation. Within today's collaborative working environment supported by the state-of-the-art information technologies, the way of undertaking knowledge management in engineering design may have changed from the traditional way of recording useful data and information that can be codified. New methods and models are required to meet these changes and provide viable solutions as well as to develop new computer support tools. The methodology of this research should step from this background and address the characteristics of design research mentioned above.

The research question of this study is “how to capture and represent design knowledge and experience during a collaborative engineering design process for effective reuse”. In order to answer this question, the methodology of this study can be divided into three parts, i.e. requirement analysis, development of methods and models, and implementation of a prototype system. Specifically, in terms of requirement analysis, this research should find out what kinds of data, information and knowledge will be generated during an engineering design project together with the differences between these three elements, as well as what are engineers’ information needs and information-seeking behaviours within a collaborative working environment. This part of research is to improve understanding, which can be done by reviewing existing literature and undertaking a survey study in real-world engineering design projects. Following this, another part of research attempts to provide methods and tools to improve the current situation, which include two parts, namely the theoretical method and the practical tool. The theoretical method is to explore the effective and useful methods for the capturing, representing and reusing design information and knowledge. The practical tool focuses on designing and developing computer support tools, i.e. a knowledge management system, for the implementation and evaluation of the proposed methods. Details of these three parts will be described in the following sections.

### 3.1.2 Literature review and survey study

In order to solve a problem, its background information and overall structure should be firstly understood. As such, the existing literature on knowledge management in engineering design, studies of the information needs and information-seeking behaviours of engineers, knowledge representation and reuse, computer support tools for knowledge management and knowledge management in collaborative working environment should be reviewed. The key objectives for reviewing related work in these areas include: (1) understanding the differences between knowledge management in engineering design and general knowledge management in an organisation as well as the important issues need to be concerned; (2) identifying and clarifying design engineers' information needs during the design process together with their ways of accessing information; (3) finding out possible models which are useful and can be partly used for knowledge representation and reuse in this research; (4) analysing the existing computer support tools for knowledge management and concluding the important functions fulfilled by these tools; and (5) exploring the ways of supporting knowledge management within a collaborative working environment.

Based on the literature review, a survey study can be undertaken in an engineering design project. The purposes of the survey study come from two parts: one is to prove certain conclusions from the previous literature; and another one is to explore new findings. The survey subject should be familiar with the newly-developed information technologies and Web-based systems whilst having great interest and demand in using computer support tools to assist their knowledge management tasks. The survey study can be arranged into two phases, namely an informal interview and a questionnaire. The interview method is chosen as it is a straightforward way of obtaining basic information and the informal structure allows the engineers to response naturally. The questionnaire is chosen as a structured way to derive desired information based on a set of questions to be answered by the subjects, which ensures the information obtained can be further organised and analysed. In this case, the informal interview is used to collect the general ideas about the background of the engineering design project, basic statuses of the engineers and their possible requirements. With these kinds of information, a questionnaire is designed and delivered to the project team members. The questions asked in the questionnaire are focused on engineers' information needs and information-seeking behaviours, their ideas about what kinds of functionalities a computer support tool should have for knowledge management in the design project, as well as their opinions on the importance of design data, information and knowledge and the main means of reuse. The result of the survey study will be analysed and compared to existing literature to identify differences and new trends, and on this basis will provide ideas for other parts of this research.

### 3.1.3 Theoretical method

Combining the results from the literature review and the survey study, the key issues on supporting design knowledge capture and reuse can be identified. Then, information and knowledge models are proposed to deal with these issues theoretically. At this phase, the Design Research Methodology proposed in (Blessing & Chakrabarti, 2009) is used as a reference for guiding how to generate a model for solving the above issues: (1) to analyse the overall requirements and the problems to be solved; (2) to explore possible methods from previous similar studies; (3) to integrate the optimal method within this problem-solving context to obtain a desired model; (4) to evaluate the model with practical engineering design example for improvement; (5) to generate the a systematic method for the application of the model. The requirements and problems to be solved are set in the context of knowledge management in engineering design. The existing methods that can be potentially useful are normally not generated for this specific area, e.g. some design models. However, a part of the methods within these models can be helpful within the knowledge management context. Thus, these useful methods can be integrated together with several new factors specific for the set context to generate a complete method. The newly-created method should be evaluated using practical engineering design examples to evaluate its strengths and weaknesses, and then some further improvements can be undertaken. In this way, a complete method covering the whole procedure of capturing, representing and reusing design knowledge for an engineering design project can be obtained and described in a systematic way for further study and application.

### 3.1.4 Practical tool

This part of research focuses on designing and developing computer support tools to apply the theoretical methods proposed. The methodology of this phase refers to the Methodology on Computational Design Tool Research (Bracewell, Shea, Langdon, Blessing, & Clarkson, 2001). It specifically has five steps: (1) requirement analysis based on the results of the literature review and survey study; (2) design and construction of the system architecture according to the information and knowledge models proposed; (3) analysis of the enabling technologies and development of the system based on its architecture; (4) test and evaluation of the system in engineering design projects; (5) improvement of the interfaces and functionalities of the system. The literature review has provided the main characteristics of the existing knowledge management system and some of them should be absorbed by the system to be developed in this research. At the same time, the results from the survey study reveal the key issues in supporting engineers to meet their information needs effectively, which should be considered in the development of the system's main functionalities. The information and knowledge models proposed should be placed in the central position in the design of the system architecture as the system is used to provide the practical implementation for the models. In terms of the enabling technologies, as the rapid development of information technology, it is impossible to use the newest ones. Thus, the focus on this research is to find out the new technologies that can best implement the proposed functionalities of the system. The system will be evaluated in different engineering design projects to test its performances in various areas. Based on the test and evaluation results, the system can be improved regarding to its interfaces and functionalities.

## 3.2 Research Project Procedure

With the methodology discussed above, this research project can be divided into three main parts, as shown in Figure 3.1. Firstly, a literature review on knowledge management in engineering design, engineers' information needs and their information-seeking behaviours, knowledge representation and reuse, computer aided tools support for knowledge management and reuse, and knowledge management within a collaborative working environment will be conducted. Then, a survey study will be undertaken in a Formula Student racing car design project, together with the literature review results to identify the key issues for the research.

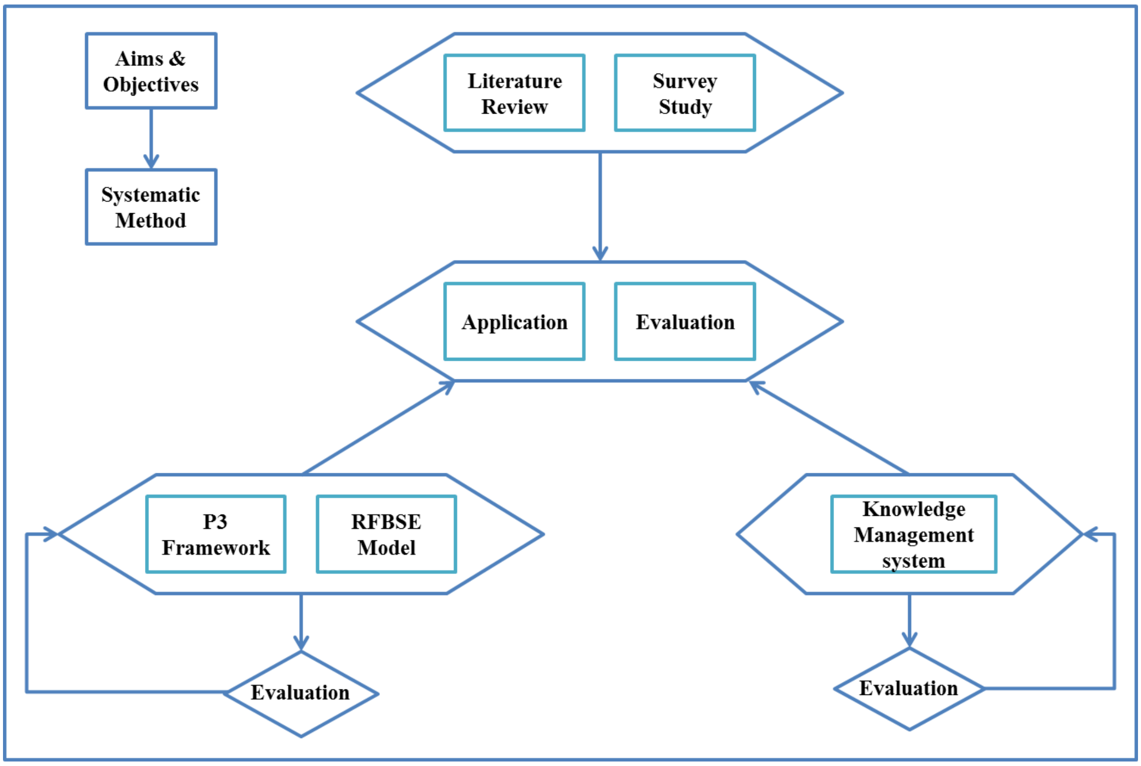


Figure 3.1. A plan for the methodology employed in this research

Secondly, a Product-Process-Project (P3) framework is proposed to consider how to classify and organise the useful information and knowledge within an engineering design project. Then, a Requirement-Function-Behaviour-Structure-Evolution (RFBSE) knowledge representation model is developed to capture and represent design knowledge alongside the design process for future reuse. Thirdly, a Web-based knowledge management system is designed and developed with its system architecture designed based on the P3 framework and the RFBSE model. The enabling technologies of the system include state-of-the-art Web development technologies, such as HTML5, CSS3, JavaScript, jQuery, KineticJS, PHP and MySQL. Afterwards, the RFBSE model is applied in an engineering design project and compared with several existing models for evaluation. Besides, the system is tested and evaluated in three different types of engineering projects. The first one is an intake system design from the Formula Student racing car design project, identifying how to capture and represent the design information and knowledge through the design process. The second one is an engine water-jacket mould design from an engine manufacturer, demonstrating how to capture the valuable design knowledge from the design improvement process based on testing and simulation. The third one is an oil head maintenance project from a hydropower station, explaining why the system is useful in capturing important information and knowledge throughout a maintenance task. To summarise, this research is divided into four main tasks mentioned above and the details of these tasks are described in detail in Chapter 4 (literature review is discussed in Chapter 2), 5, 6, and 7, respectively.

# Chapter 4

# Information Needs and Information-Seeking Behaviours of a New Generation of Engineers

## 4.1 Designers' Information Needs and Information-seeking Behaviours

During engineering design projects, engineers require various kinds of information to support their decision-making especially at the conceptual design stage. This information can be in the form of some empirical results from previous projects, advices from senior colleagues, and requirements specified in the design specification. Understanding what kinds of information is required by engineers and how they generally seek information is the basis of providing effective support to them. In this way, design efficiency can be improved by quick access useful and relevant information. Therefore, studying the information needs of engineers and exploring how to support their information-seeking behaviours has become a research topic. From existing literature in these areas, engineers spent a large amount of time seeking for proper information everyday through different sources (Hicks et al., 2002). Thus, providing information to engineers in response to their requests is an efficient way can certainly improve design efficiency. Another significant issue comes from novice engineers, who tend to have difficulties in judging what kinds of information will be useful as well as in subsequently looking for the useful information they need (Ahmed & Wallace, 2004). Usually, these novice engineers will turn to senior colleagues for help. However, the senior members are not always available especially in the context of big companies that involves large-scale global projects. In this case, a knowledge management system which can not only organise the design data and information but also capture the design knowledge and experience will be essential to support knowledge transfer and thus provide guidance to novice engineers.

Within nowadays' highly developed information technologies, the information-seeking behaviours of engineers in fulfilling their information needs are affected. Also, the requirements for collaborative working in different project teams and distributed working environment raise new issues to be considered in the research on engineers' information needs and information-seeking behaviours. Therefore, based on this situation and the two issues raised in literature, a survey study has been undertaken aiming to underpin this research by investigating how to better meet the information needs of next-generation design engineers who prefer to work in a distributed and collaborative manner and use advanced information technologies to support their tasks. It was undertaken in an engineering design project to explore the information needs and information-seeking behaviour of the engineers in the project team. The results of the study have been analysed and compared to the results from the previous literature to obtain new ideas on developing a new generation of knowledge management system which can capture useful design knowledge and experience of engineers through the design process for future reuse.

## 4.2 Survey Study Design

### 4.2.1 Study subject

The subjects chosen for this study are from the Formula Student racing car design project in the University of Portsmouth. The considerations of choosing this project come from various aspects. Firstly, it is a complete engineering design project, which starts from design specification to conceptual design, embodiment design, and detailed design, then to manufacture, testing and finally the competition. In addition, the Formula Student project is Europe's most established educational motorsport competition, run by Institution of Mechanical Engineers (IMechE), which makes the project demanding and close to the industry-level projects. Secondly, this project continues every year. In this sense, knowledge transfer within the project team members becomes significant as old members need to pass their knowledge and experience to new members (who generally have very limited expertise in this automotive design area) in the following year before they leave the project team. Thirdly, these project members are university students doing engineering courses who can be regarded as the future engineers, and they are novice engineers that are more easily to be guided and supported. More importantly, they are more familiar to the newly developed information technologies and are thus more likely to try the new computer support tools powered by these technologies.

### 4.2.2 Study procedure

The survey study has two parts, namely the informal interview and the questionnaire. The former is undertaken individually with the project members with the purpose of gathering basic information for the questionnaire questions. Also, the interview happened during project team weekly meetings and section discussions. Through both ways, general information on ‘what are their daily tasks’, ‘how do they access and manage data and information’, ‘have they reused previous designs’, ‘how can new members learn design knowledge from previous and current projects’, etc. has been obtained.

With this information, a questionnaire consisting of 15 questions has been designed and delivered to the Formula Student project team with a group of 30 members. These questions specifically focus on four aspects. Firstly, the subjects will be asked about what are their daily tasks, and in order to complete these tasks what kinds of information and knowledge will be required. Additionally, they are also asked whether these information needs are different comparing between the time when they first joined the project and the time when they became more familiar with the project. Secondly, questions on what types of information they deal with when they are undertaking daily tasks during the project and how do they obtain them are also asked, together with the question on how will they store and share the useful information. Thirdly, the subjects will be asked about their opinions about using an information/knowledge management system for helping them meet their information needs and what kinds of functionalities the system should have. Fourthly, questions on what kinds of design information should be reused and what kinds of knowledge is the most useful for effective understanding and reusing of previous designs will be asked. Through these four aspects of questions, the information obtained from the answers can be analysed and used to compare with the results obtained from previous research in the literature. Also, new ideas can be generated from the survey results on how to support engineers, especially novice engineers to fulfil their information needs and support their information-seeking behaviours, as well as giving ideas on the design and development of the next-generation knowledge management systems.

## 4.3 Survey Results and Analysis

The results of the survey studies are analysed with four particular focuses, i.e. information needs, information-seeking behaviours, knowledge management, and information and knowledge reuse. The results of the survey and the analysis of these results will be discussed in the following sections.

### 4.3.1 Information needs

The daily tasks of the project members were firstly asked to identify how they are related to the transfer and processing of information. The results obtained have been summarised in a way to show how much effort they spend on different tasks, as shown in Figure 4.1.

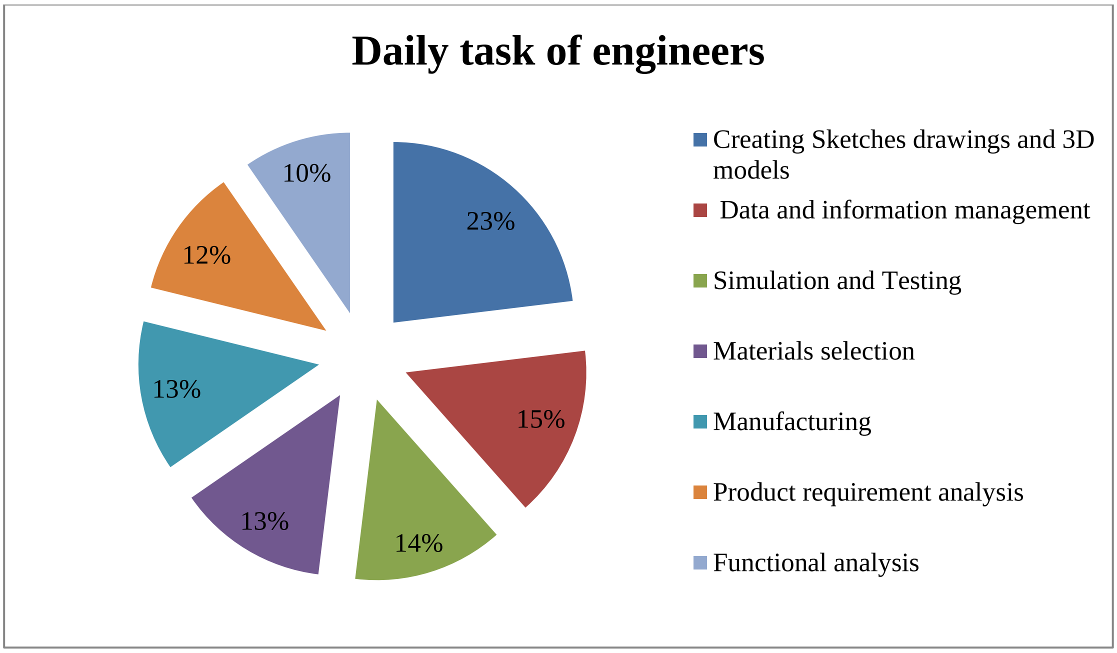


Figure 4.1. The daily tasks of the Formula Student project members

From Figure 4.1, the tasks undertaken are across the whole engineering design process, among which around half of the time is spent on conceptual design including requirement and functional analysis as well as creating sketches, drawings and models. The reason why the survey subjects spent such a large amount of time undertaking the tasks for conceptual design is because the conceptual design stage is significant in the sense that it links requirements analysis and functional analysis and as a result affects the following stages of generating embodiments (Pahl et al., 2007). During this stage, engineers need a large amount of information and knowledge to support their idea generation and decision-making (Heisig et al., 2010), which indicates the engineers have large information needs at this stage. The following stages, namely materials selection, manufacture, simulation and testing, account for about 40% of the total tasks. The information needed for these processes is varied, which may be obtained from previous projects, e.g. engineering drawings, 3D CAD models, manufacturing methods and simulation results. Interestingly, 15% of the daily tasks related to data and information management in order to provide useful information for the other tasks. This result stresses the importance of obtaining, storing and sharing information for an engineering design project, which is also corroborated by Baxter et al. (2008)'s study. Also, this result reveals that increasing the efficiency of obtaining useful information can help to improve the efficiency of the whole engineering design project.

As a design project can last for a long period of time, the information needs for engineers may vary at different stages. The survey study has also explored this area with the focus on finding the differences and providing different kinds of information support accordingly, as results shown in Figure 4.2 and 4.3. Apparently, the engineers are more focused on background information (16%) and design specification (11%) of the project when they first joined the project, compared to the 4% and 6% in the later stage. When engineers first join a project, they are focus more on general information about the project in order to obtain a good understanding of the project status and the areas they will work in. As they are getting more familiar with the project, they turn their attention into more detailed information, e.g. solutions for issues and problems (13%), budget and resources (17%). Previous design solutions, particularly design rationale, become more valuable when engineers start to concentrate on specific design issues. In this case, what engineers need is not only previous design data and information, but also the relevant design knowledge in order to fully understand previous design solutions. These kinds of design knowledge normally exist in engineers' brains, which can only be well explained with the help of rich design context and fundamental knowledge. As such, it is difficult to write them down in design reports—even this is done, it is still not easy to find and locate. Therefore, the trend of how the information needs of engineers will be changing is basically from general information to specific information, and the key for finding the specific useful information and reusing it depends largely on the design knowledge in engineers' brains. In this case, supporting tools, such as a knowledge management system which can capture such design knowledge for reuse, will be significantly useful.

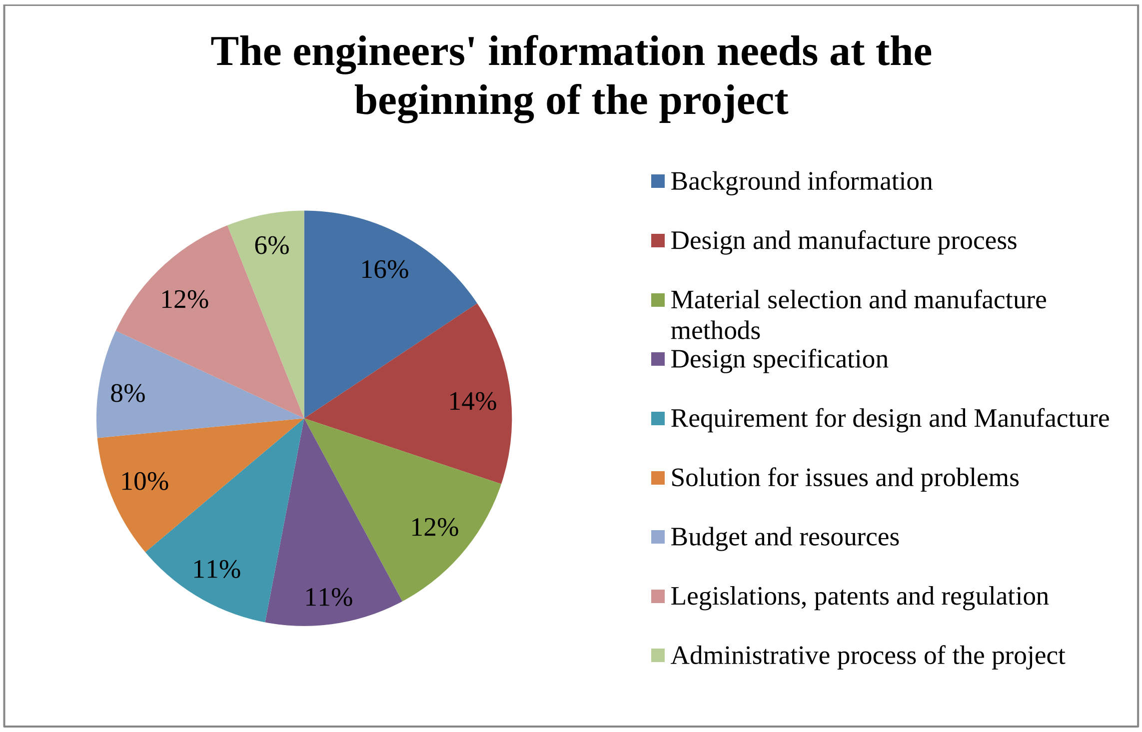


Figure 4.2. The engineers’ information needs when they first joined the project

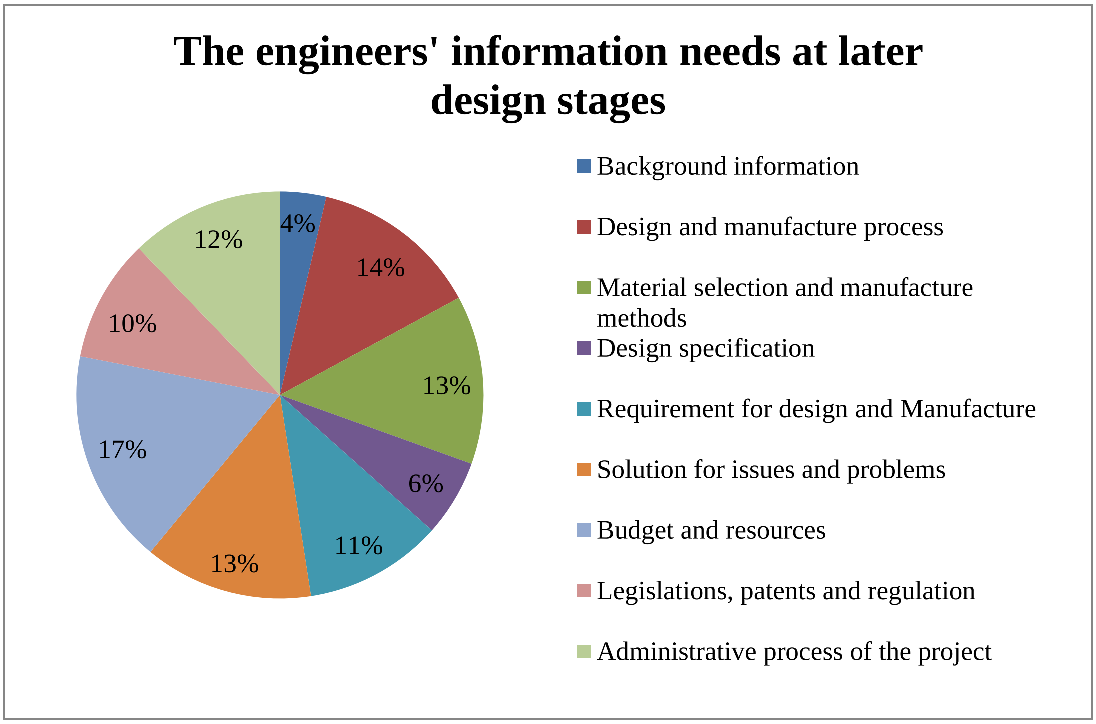


Figure 4.3. The engineers’ information needs when they are undertaking the project

Apart from these differences, the needs for information on the design process and the methods for material selection and manufacture almost remain the same, indicating that engineers have constant information needs in these areas. The project members can mostly be regarded as novice designers and thus these results have also identified some important aspects in order to provide support to novice designers. As novice designers generally do not have a clear strategy in obtaining information for design tasks (Ahmed & Wallace, 2004), providing a systematic method, i.e. information/knowledge representation model, to guide them to organise the information and knowledge is necessary.

### 4.3.2 Information-seeking behaviours

The survey subjects are university students who have been trained in using various design and analysis tools and more importantly they are familiar with newly developed ITs. The familiarity with advanced information and Internet technologies is a distinct character of this new generation of designers. In this sense, their information-seeking behaviours may be to some extent different from the older generations of engineers. The survey results have also revealed some details about this. The information-seeking behaviours of the subjects have been observed and analysed by asking several questions, with the main results shown in Figures 4.4 and 4.5.

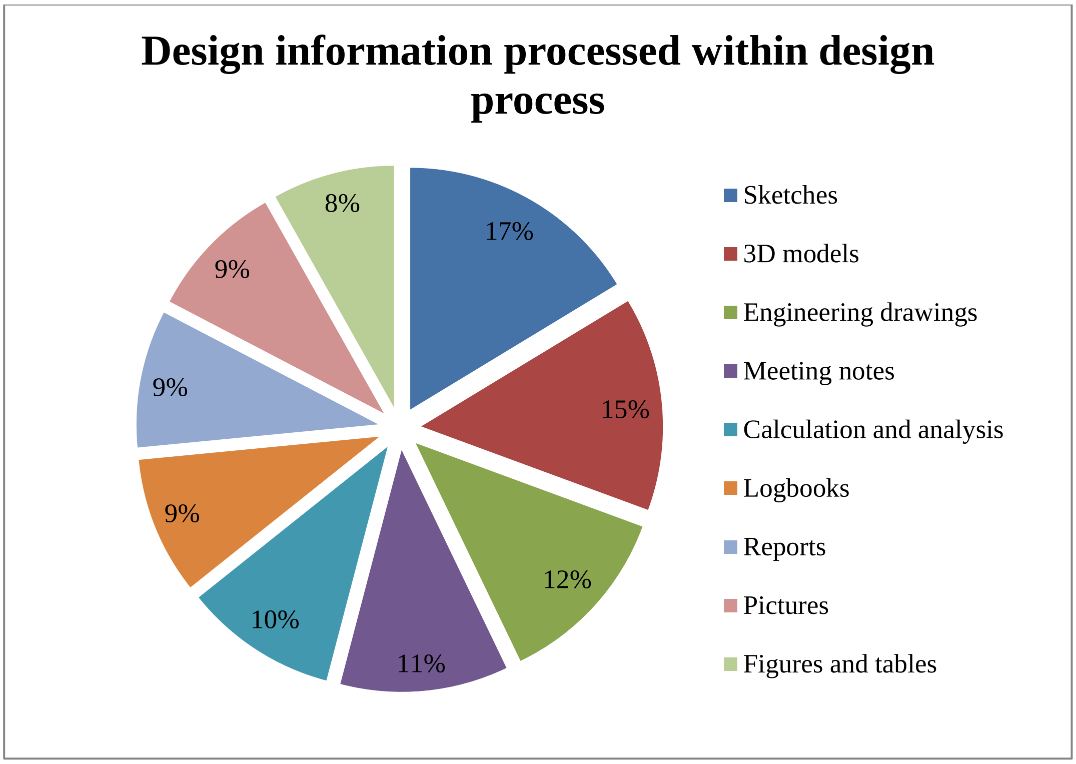


Figure 4.4. Information processed in design tasks

It can be seen from Figure 4.4 that sketches, engineering drawings and 3D models are the types of information the engineers most frequently deal with. These types of information can be easily organised and stored as electronic documents in a computer. However, simply storing them in electronic files may not enable them to be reused effectively, as it is difficult to find a specific piece of information from a large number of files. This thus raises the needs of using a knowledge management system to provide a systematic way of storing information as well as powerful functionalities of information/knowledge representation and retrieval. Moreover, with a knowledge management system, calculation and analysis results, pictures, and figures and tables can be well organised and stored in the system for effective reuse. There are other types of information coming from meeting notes, logbooks, and reports which are generally paper-based. These paper-based documents are also important information sources as tacit design knowledge might be recorded in these paper-based documents for undertaking causal analysis and explaining decision-making processes. Thus, these documents are essential to be stored for future reuse. However, they are paper-based documents and a lot of them are personal properties, which makes them difficult to be shared and reused. In this case, transferring this tacit knowledge into a knowledge management system is a good solution, as the system can provide a better environment for sharing and reuse.

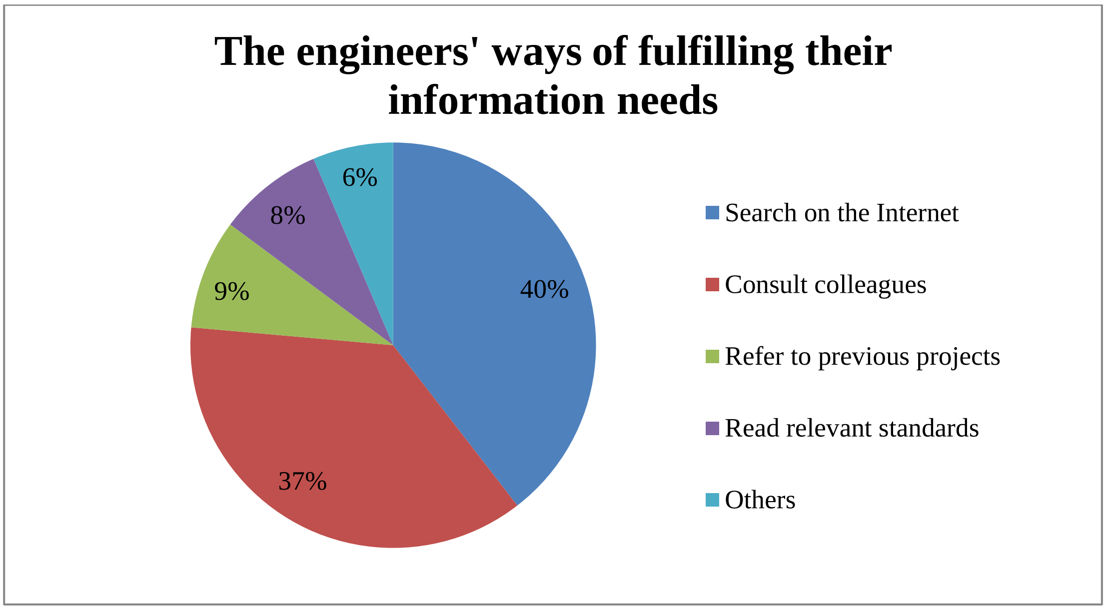


Figure 4.5. Ways of obtaining information

Figure 4.5 classifies the different ways of seeking information by the engineers. Consulting colleagues for information is still a main method for the engineers to obtain information, which is largely corroborated by previous studies (Kwasitsu, 2003). However, the percentage of fulfilling information needs in this way (37%) has turned out to be much lower than the percentages found in previous studies, e.g. 90% in Marsh's study (1997) and 70% in Aurisicchio's study (2004). Compared to the information-seeking behaviours identified 18 years and 11 years ago, the engineers' information seeking behaviour is heavily affected by the Internet and advanced ITs. With the rapid development of these technologies, utilising the Internet and specialised

IT systems has played an increasingly significant role in seeking important information. According to the result of this survey study, 40% of engineers’ information-seeking activities are related to searching on the Internet and Information/knowledge management systems. As the survey subjects are regarded as a new generation of design engineers, this result thus reveals that the information-seeking behaviours of future design engineers will be strongly affected by the Internet and Web-based systems.

### 4.3.3 Knowledge management

With Web-based technologies becoming more mature and reliable, the information and knowledge management tasks in design projects can be undertaken more efficiently using Web-based knowledge management systems. In order to figure out what kinds of functionalities these systems should have and how these the systems should undertake the information and knowledge management tasks, the survey study has explored engineers’ ways of managing and sharing information, as well as their opinions on the functionalities of the next-generation knowledge management system, with the results shown in Figures 4.6, 4.7 and 4.8 respectively.

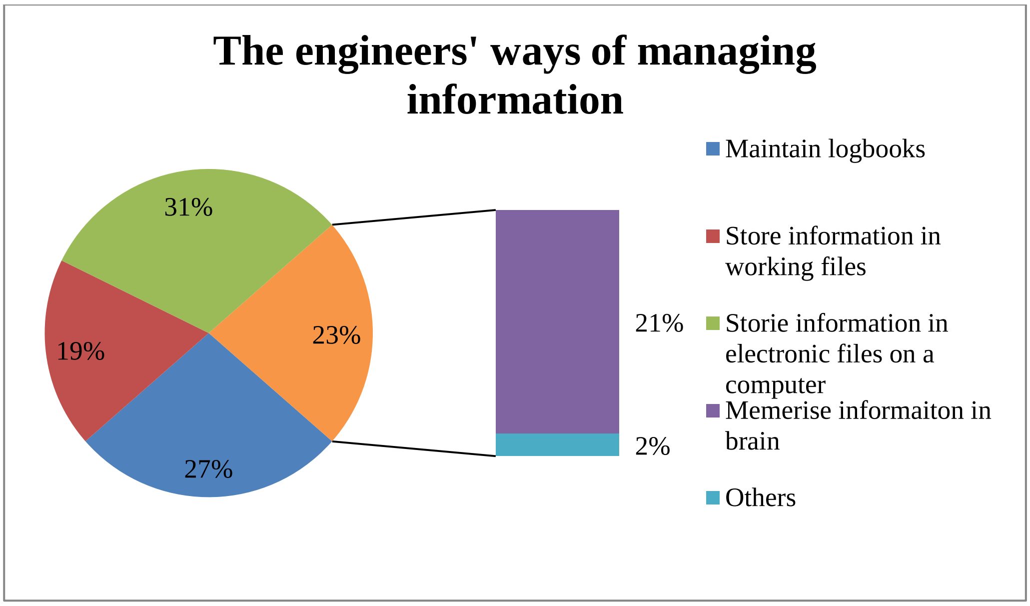


Figure 4.6. Different ways of managing information by engineers

Figure 4.6 shows the ways of managing and storing information by the engineers. Among these different ways, using electronic files on computers is a major way for storing information (31% of the information). As these files are computer-based, they can be easily organised and stored in knowledge management systems. Recording information in logbooks and working files are another two important ways of managing information by engineers. Logbooks and working files are traditionally paper-based, and, in order to organise and share the information recorded within them more efficiently, it is better to transfer the information into knowledge management systems. Normally, working files are used for recording structured information while logbooks are usually used for informal information. Thus, the next-generation knowledge management systems should have the functionality of recording both structured formal information and unstructured informal information. Apart from these, a large amount of information is memorised in engineers' brain, which is thus called their personal experience and knowledge. For this part of information, it is not easy to share if it only exists in engineers' brains. In this case, the knowledge management system should provide a way to capture and record these kinds of information and knowledge for future reuse.

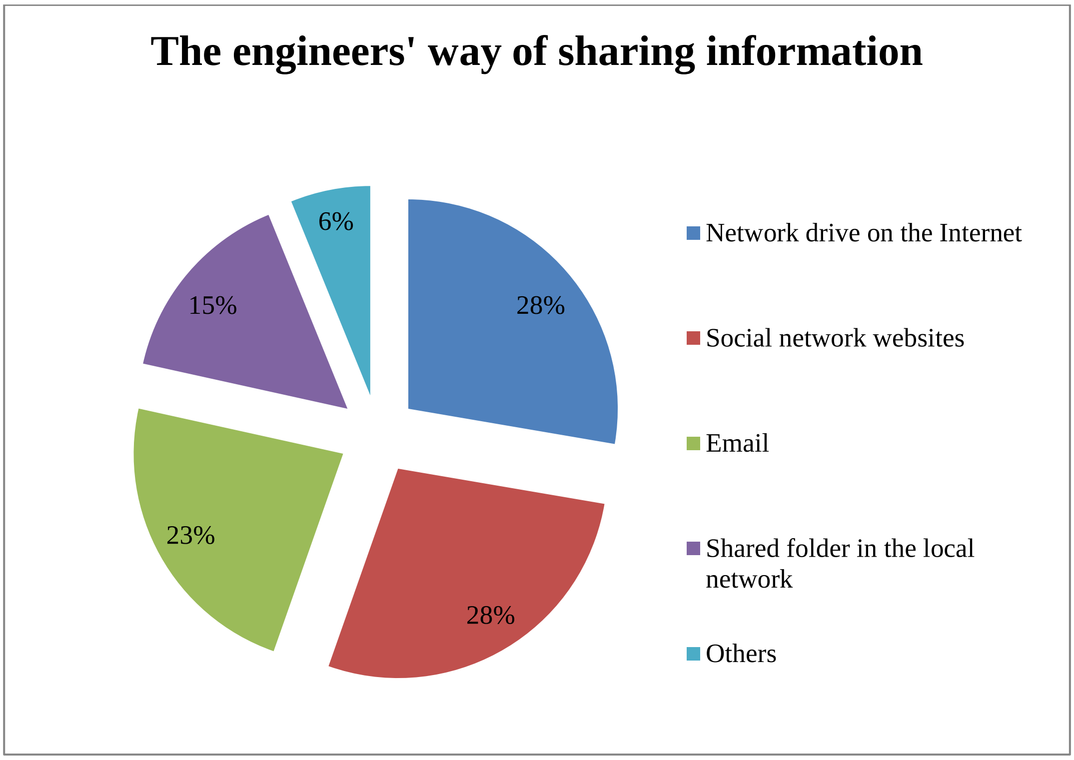


Figure 4.7. Different ways of sharing information by engineers

After analysing the engineers' means of managing information, Figure 4.7 identifies their ways of sharing it. Apparently, these future engineers prefer to use various Web-based tools to share information, especially in a distributed working environment. Network drive (28%) and Shared folder (15%) are the two main methods for the young engineers to store and share information. Also, they will communicate and share information through email (23%) and social media (28%), e.g. Facebook. The advancement of current ITs has facilitated these ways of sharing information. This reveals the trend that Web-based tools that support collaboration and information sharing are becoming more popular in storing and sharing information.

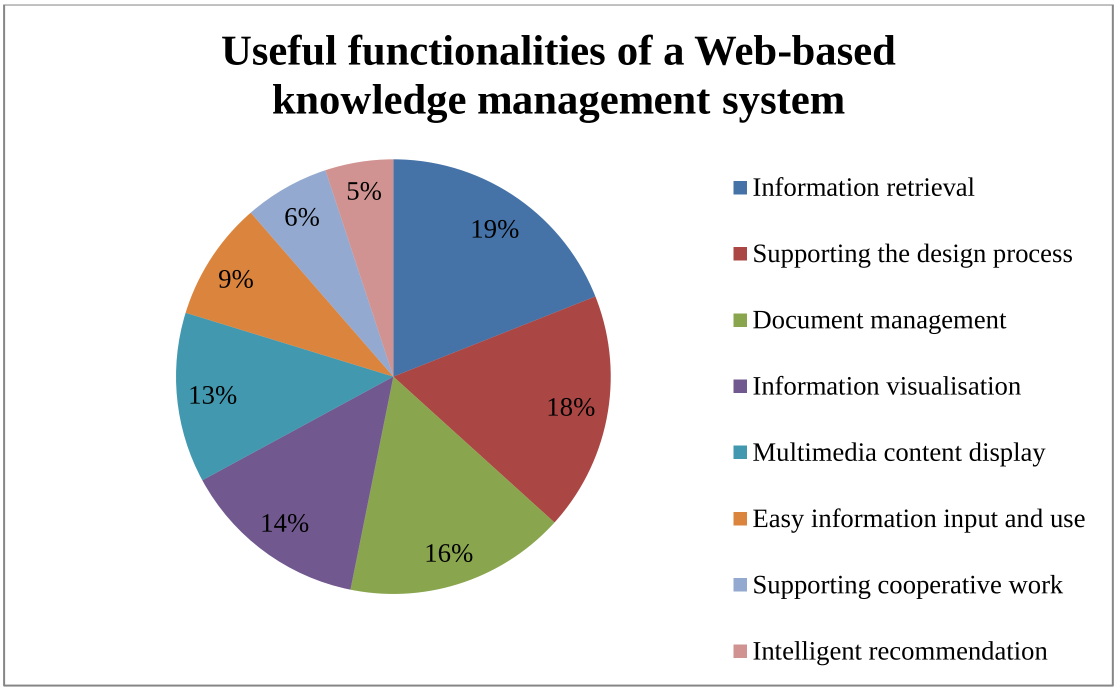


Figure 4.8. Engineers' preferences on the functionalities of the knowledge management system

Regarding to what kinds of functionalities a Web-based knowledge management system should have, opinions were obtain by the project members, with the results shown in Figure 4.8. As a knowledge management system, document management and information retrieval should be the basic functionalities. Interestingly, supporting the design process is considered as an even more important functionality, which indicates the novice engineers require lots of guidance throughout the design process. However, this functionality is a relatively new requirement that most existing knowledge management systems cannot address.

In order to achieve this functionality, a knowledge representation model that can identify and describe different pieces of knowledge generated across the whole design process is required. Besides, information visualisation and multimedia content display are other important functionalities preferred by the young engineers, as these can facilitate users' understanding of the information and knowledge captured, particularly for the complex relationships between different pieces of knowledge. The others functionalities, e.g. easy information input and use, supporting cooperative work and intelligent recommendation, are also regarded as the functionalities which can increase the system's usefulness.

### 4.3.4 Information and knowledge reuse

The ultimate goal of developing knowledge management systems is to capture and reuse design knowledge. In order to achieve this goal, what kinds of information and knowledge are useful for reuse should be analysed. Thus some questions on these aspects have been asked in the survey, with the results obtained shown in Figure 4.9 and 4.10.

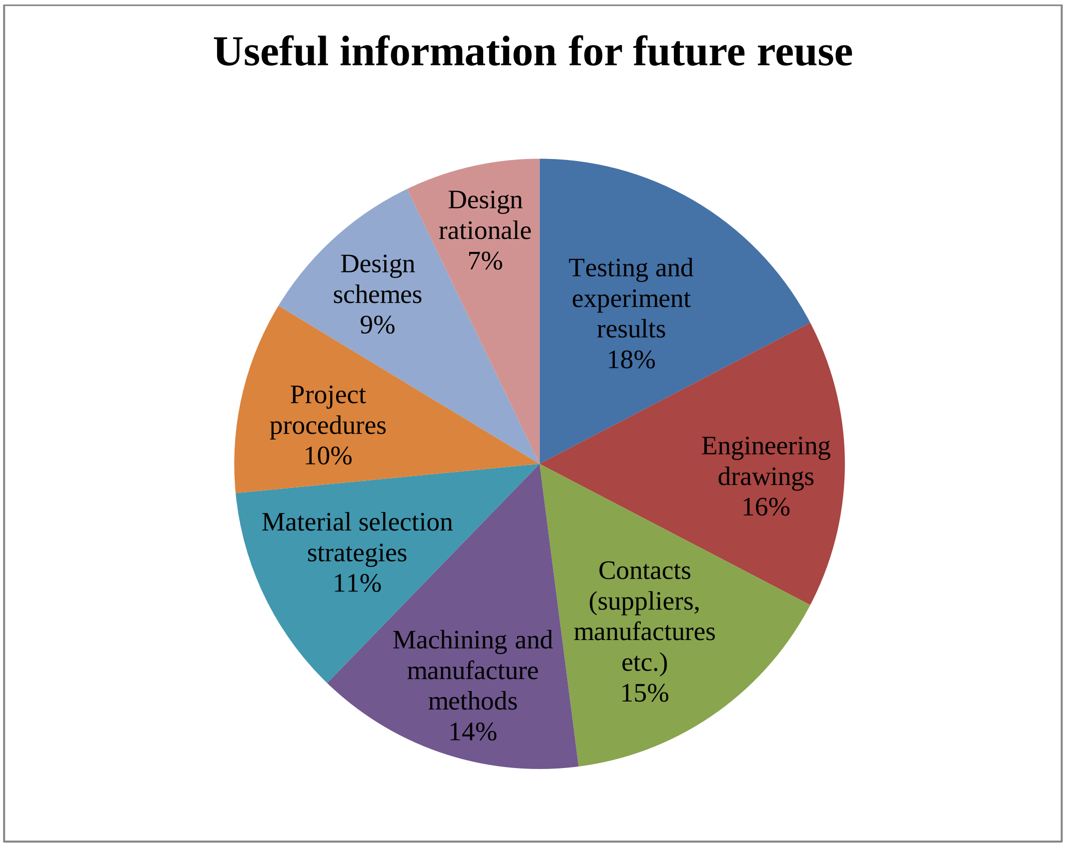


Figure 4.9. The various kind of information useful for future reuse

Figure 4.9 shows what kinds of information the project members consider as being useful for future reuse. Apparently, engineering drawings, testing results (34% together) are regarded as being useful for reuse, as they are telling the basic information of the project. Another part of information worth reusing is on machining and manufacture methods, material selection strategies and project procedures (35% in total). These kinds of information are used to describe the methods, strategies and procedures, which are about important engineering know-how. Moreover, design schemes and design rationale (16% in total) are also important for reuse, as they include the design experience and knowledge. Besides, different kinds of contacts (15%) are regarded as important information for reuse at the project level. It is acknowledged from the results that there are mainly three types of design knowledge exist and should be captured for reuse, which can be generally categorised as engineering know-what, know-how and know-why.

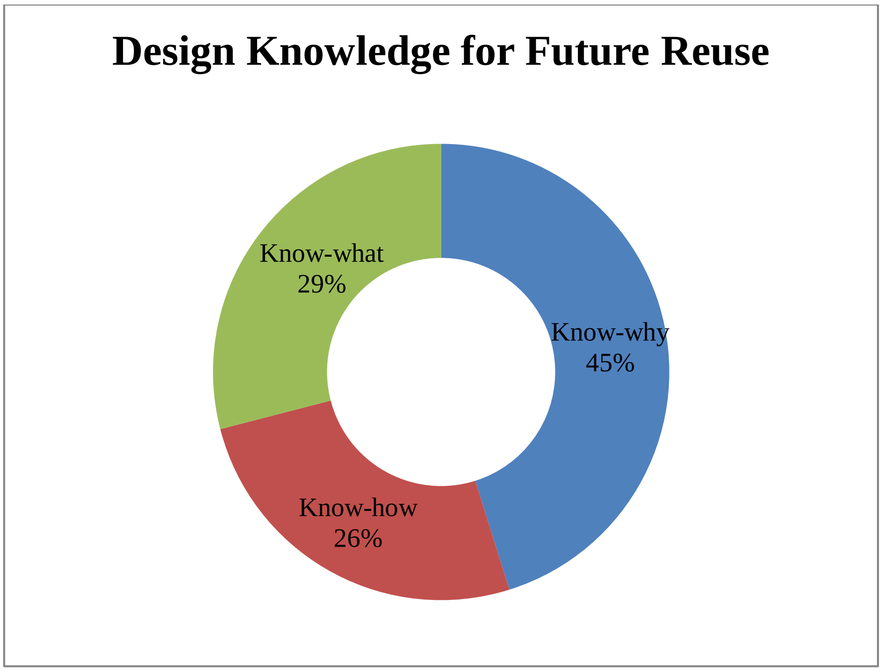


Figure 4.10. Different kinds of knowledge useful for future reuse

Referring to these three types of design knowledge, the young engineers were asked which types of knowledge they think should be most important for reuse. Figure 4.10 indicates that project members consider know-why knowledge to be the most important for reuse. This result corroborates a finding from previous research which shows the rationale or reasoning behind a design, i.e. why choices are made, is the most mentioned knowledge and information needs (Heisig et al., 2010). When the young engineers' opinions on different information useful for reuse are compared, it is interesting to find that they are aware that know-why knowledge is the most valuable one for reuse although they also focus on basic information and are interested in how to do something. Know-why knowledge comes from experience, which facilitates the capture of the relationship between engineering know-what and know-how by explaining the processes of design choices evaluation, decision-making and problem solving. Thus, know-why knowledge is the one to link different kinds of information together and make them more useful.

## 4.4 Discussion

The survey study has been undertaken in a Formula Student project, which has limitation on the survey subjects who are university students. In this case, it is argued that the results obtained provide different perspectives and findings from those obtained in the previous research focusing on engineers working in industry. Moreover, the focus of the survey study is an attempt to find out the information needs and information-seeking behaviours of next-generation engineers especially novice engineers and on this basis to develop effective methods and tools to support them. The university students can be regarded as future engineers and certainly they are novice engineers at the moment. With the highly developing information technologies, their ways of seeking information to fulfil their information needs have changed and thus are different from the older generations of engineers. Also, the university students are more flexible to try new ideas and methods on supporting their engineering project. For the next generation of engineers, it is supposed that the way of their communication, collaboration, and application of supporting tools will be different compared to the traditional engineers. Thus, their requirements on the computer support tools and their specific functionalities might be different, which makes it meaningful to undertake the study on novice engineers. Also, the novice engineers need to be guided a lot, the study on them can contribute to how to guide these engineers during the engineering design process. Besides, the Formula Student project is a complete engineering design project which is enough for this study, as this ensures the completeness of the collected information. Therefore, the Formula Student project has been selected as the research subject in this survey study.

## 4.5 Summary

The survey study has been delivered to a Formula Student racing car design project to explore the information needs and information-seeking behaviours of the next-generation of engineers. Also, the survey study has explored these aspects within a collaborative working environment where a range of Web-based information technologies have been highly developed. Even though the scale of the project is relatively small, it is a complete engineering design project, encompassing all the important stages and using all necessary industrial standards, and the subjects can be regarded as the future engineers who require a range of support when they are undertaking tasks. Thus, this survey study gives new ideas on how to support young engineers on their information needs and information-seeking behaviours, and subsequently is beneficial for developing the next-generation knowledge management systems.

The results from this survey study have implied design engineers' information needs are diverse and evolve throughout a design project, and moreover, apart from the technical data and information, such as engineering drawings and CAD models, the knowledge on decision-making such as design rationale is also significant for designers to reuse in future projects. Specifically, in an engineering design project, the design stage requires the most resources compared to the following stages. These resources include analysis results, regulations and specifications, standards, design schemes and experience, which might come from previous design projects, relevant Internet resources and engineers' memory. It is essential to collect them all in one place where they can be stored in a systematic way and then can be accessed easily. Besides, considering for effective reuse, not only the structured data and information should be recorded and organised, but also the knowledge behind them.

From the results, an integrated knowledge management system is promising for capturing design information and knowledge as well as for effectively fulfilling engineers' information needs. The system should be Web-based and support a collaborative working environment. More importantly, in order to capture the design knowledge, a knowledge representation model is required to act as the fundamental part of the system whilst the design context for the knowledge should also be recorded in order to reuse the knowledge effectively and efficiently. All of these give ideas on the following sections.

# Chapter 5

# Capturing Integrated Design Knowledge from the Design Process

## 5.1 Capture and Reuse of Design Knowledge

In an engineering design project, a huge amount of design data is generated and accumulated throughout the design process, including materials, formulas, calculation results, engineering drawings, CAD models. These data provide various types of information about design solutions and thus highly useful in the following stages of the project or in the future projects. The reuse of these data and information can be more efficient and effective if the knowledge and experience of designers on how to find, correlate, and process useful information is identified and captured. This kind of knowledge not only gives useful context for explaining why certain data and information are used in particular ways and how they can be reused, but also provides important insights into what reasoning process together with the considerations and trade-offs are involved. In this case, it is significant to capture this kind of design knowledge for future reuse.

The design knowledge is usually generated through processing the design information, and there are two main kinds of design knowledge. The first one is product design knowledge which explains how the certain designs have been undertaken, including the techniques and theories behind the scene. Another one is process design knowledge, which is explaining the reasoning process like problem solving and decision-making. Unlike design data and information, design knowledge is difficult to be captured and structured, as it usually resides in engineers' brains. Therefore, there is a research gap to address the integration of the formal design data and information and the tacit knowledge to represent in an integrated knowledge space.

Currently, the commercial knowledge management systems are mainly used to organise and store design data and information about design solutions in a database or repository for reuse. However, these systems predominantly focus on the storage of data instead of their reuse, while they can hardly capture the design knowledge and experience as there is a lack of guidance and support for describing and capturing the knowledge through which design solutions are generated and evaluated. To provide guidance and methods for capturing design knowledge, particularly the tacit knowledge about interpretation of information, design synthesis and decision-making, integrated knowledge models are required. Some previous efforts have been made to address certain aspects, including the FBS design schema (Gero, 1990) for describing the function, behaviour and structure of design objects, the SBF model for analogical design (Bhatta & Goel, 1994) and the Design Rationale Editor for capturing design rationales (Bracewell, Wallace, Moss & Knott, 2009). However, these models or tools are mainly focused on a particular part such as design objects or design rationale. Thus, new knowledge models are needed to describe and represent knowledge space involving design objects, problem solving processes and decision-makings.

To develop an integrated knowledge model for effectively capturing design knowledge, the main characteristics of design knowledge should firstly be identified and analysed. There are three main aspects of design knowledge in terms of its capture and reuse, namely knowledge category and topic, knowledge hierarchy and context, and knowledge scope and its information granularity. Specifically, knowledge category and topic helps to classify different kinds of knowledge in order to make them more easily found and understood especially for tacit knowledge; Knowledge hierarchy considers the levels of, and the relationships between, different pieces of knowledge, such that they can provide contexts for each other and can be aggregated into 'bigger' knowledge elements; Knowledge scope and its information granularity determines how detailed a piece of knowledge is. These characteristics indicate the important areas that should be considered when developing a method to capture and reuse design knowledge.

The method developed in this research has considered these characteristics, and has concluded the procedure into three steps: firstly, find out where the useful knowledge exist; secondly, understand the knowledge and represent it in a structured way; and thirdly use the knowledge. Two models have been proposed to support these three steps, with specific focuses on different tasks. The first model is Project-Process-Product (P3) framework, which provides a systematic framework to classify and organise the useful information and knowledge within a collaborative working environment. The second model is the Requirement-Function-Behaviour-Structure-Evolution (RFBSE) knowledge representation model, which focuses on providing a method to capture, represent and reuse design knowledge and experience during the engineering design process. The functions of these two models can be described using an example of finding useful information and knowledge from a book in the library. The P3 model provides a framework to be used for finding out a specific book in a library, whilst the

RFBSE model is used to find out the specific information and knowledge from the book. In this case, the P3 model helps to build the infrastructural framework, while the RFBSE model is used to undertake the core knowledge capture function.

## 5.2 The Product-Process-Project Framework

### 5.2.1 Overview

With the highly development of the Internet and the Information and Communication Technologies (ICTs), undertaking engineering projects within collaborative working environment has become the trend. A collaborative working environment can support engineers in their individual and cooperative work regardless their geographical locations, and allow engineers to provide and share information and exchange view in order to reach a common understanding. However, the data and information generated within this collaborative working environment is even more enormous and complicate, as it combines various processes and people from different disciplines. In order to find out the useful information and knowledge generated collaborative engineering design process for future reuse, a systematic framework is required to identify where the useful information and knowledge may exist and classify them in a structured way. In this case, the P3 framework is proposed to undertake this task.

The P3 framework consists of three sub models, namely Product model, Process model and Project model. The Product model considers how to decompose an artefact or component into sub-sections or sub-components in order to classify the specific information and knowledge related to them. Also, the Product model highlights several areas where the useful information and knowledge most likely exists. The Process model focuses on the information flow through the engineering design project, which is proposed based on the classical engineering design process (Pahl et al., 2007; Pugh, 1991). Thus, the Process model can identify which stage the useful information and knowledge located within the whole engineering design process, and capture the process knowledge on decision makings and problem solvings. The Project model organises useful information and knowledge related to the project management, which is more focused on capturing the knowledge about how to undertake a project as well as the relationships between this kind of knowledge and the product design knowledge. Through these three sub models, the useful information and knowledge of a whole engineering design project can be classified and organised in a systematic way. Besides, within the collaborative working environment, 'People' is the key that generate and share information and knowledge, thus it is located in the central of the P3 framework, as shown in Figure 5.1.

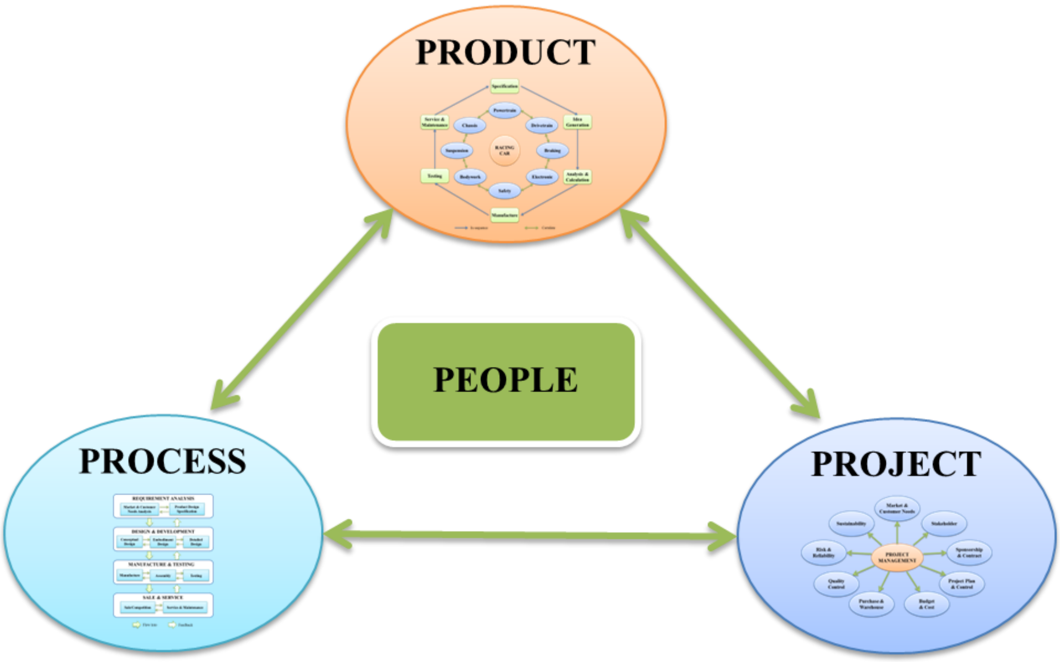


Figure 5.1. Product-Process-Project framework

Moreover, the P3 framework provides a way to allow people from different part of an engineering design project collaborate together according to its three sub models. Aa the collaboration within an engineering design project has two ways, the horizontal collaboration within same section and the vertical collaboration across various departments. Thus, the people involved are not only the design engineers, the other engineers from upstream and downstream of the design process should also be considered, as well as the management and sales people, as shown in Figure 5.2.

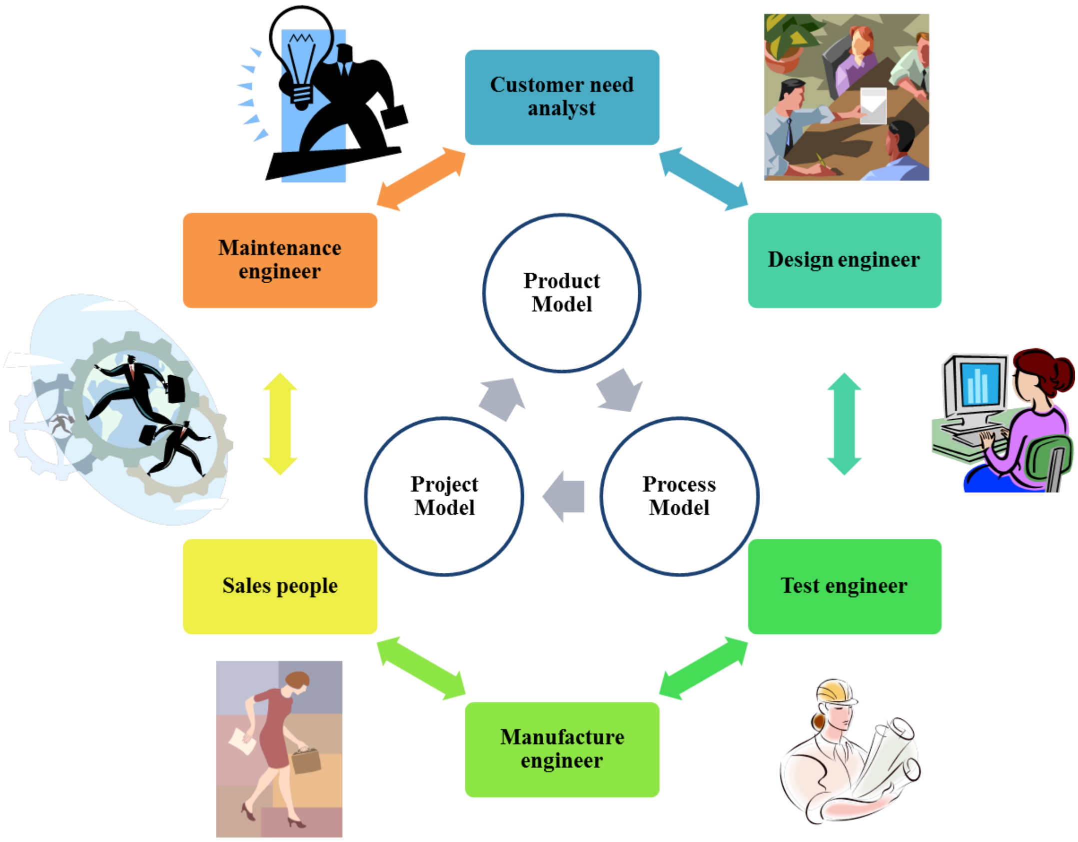


Figure 5.2. Clarifying information and knowledge in collaborative working environment by P3 framework

In this case, the P3 framework provides a platform to allow these people to organise and share their useful information and knowledge with each other. They have the same overall project goal but focus on different areas. In other words, what they are doing is related. Within this situation, the collaboration should be considered in a broader view, as listed in Table 5.1. For instance, during the customer needs analysis, the analysts will discuss what they found from the marketing research with the design engineers to determine the requirements of a new product. Moreover, the design engineers need to discuss with the manufacture engineers to determine whether a design is feasible for manufacture. Besides, maintenance engineers and sales people will provide useful feedbacks to design engineers for better suggestions on improving the artefacts or components.

Table 5.1. P3 framework and collaboration

| P3 Framework | Area of Consideration | Participants of Collaboration | Examples of Details Task |
|---|---|---|---|
| Product Model | Structural Decomposition | Design engineer, Manufacture and Test engineer | Analysis how many parts of an artefact or a component should be divided into |
| | Knowledge Hierarchy | Design engineer and Project manager | Discuss how to classify the useful information and knowledge generated during design process in order for future reuse |
| Process Model | Requirement Analysis | Customer need analyst & Design Engineer | Conclude the key customer needs and figure out how to meet these needs through the product to be designed |
| | Product Design and Development | Design engineer, Manufacture engineer & Test engineer | Feasibility analysis on the design to check whether it is suitable for manufacture, and explore the optimal way for its production |
| | Manufacturing and Testing | Manufacture engineer, Test engineering & Design engineer | Undertake simulation and prototype testing to check the possible issues on products' manufacture |
| | Sales and Maintenance | Sales people, Maintenance engineer & Design engineer | Provide customers' feedbacks during the product's usage to design engineers to find out the solutions on maintenance and design improvement |
| Project Model | Project Consideration | Customer need analyst, Design Engineer & Project manager | Set the boundary of the project, including cost, equipment, materials, etc. |
| | Project Development | Project manager, Design engineer, Test engineer & Manufacture engineer Design engineer | Provide resource and support to product design and development process, and control the project progress |
| | Project Quality | Project manager, Design engineer & Manufacture; Sales people, Maintenance engineer & Design Engineer | Analyse the risk and reliability of the product, and check its sustainability |

Within this complex collaborative working environment, the efficient and effective information and knowledge sharing between different participants becomes crucial. The P3 model aims to provide a systematic framework to organise the useful information and knowledge generated and sharing during this collaborative working environment for their effective reuse. The details of how to apply the P3 framework will be described in terms of its three sub models in the following sections, as well as an explanation on the integration of these three components to perform the overall function of the P3 framework.

### 5.2.2 Product model

The Product model concentrates on artefacts and components, aiming to capture useful information related the design and development of these artefacts and components. It firstly explores how many sections and components a product can be divided into through its physical structure, i.e. identifying the components of which the product is composed and on which the knowledge capturing task can be undertaken. As a primary example for understanding knowledge needs and knowledge objects for this research, the racing car design project is chosen as an example to demonstrate this model, as shown in Figure 5.3.

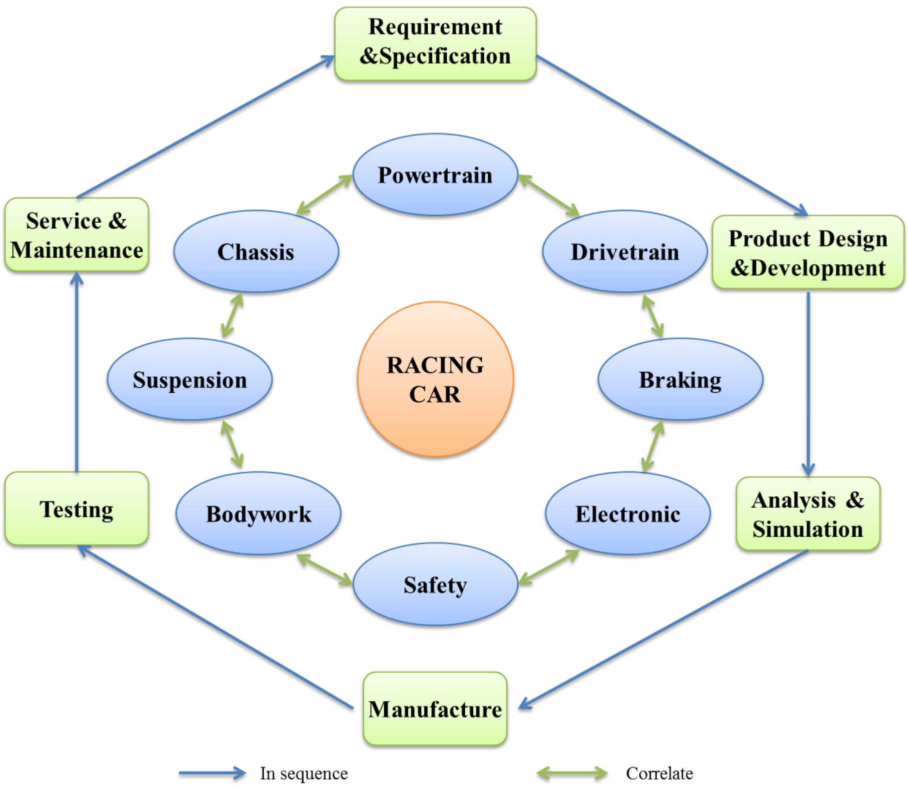


Figure 5.3. Organising product data and information by Product Model

From Figure 5.3, the racing car has been divided into eight sections according to their specific functions and physical structures, namely powertrain, chassis, drivetrain, suspension system, braking system, bodywork, electronic system and safety system. This is the first level decomposition, and further decomposition can be undertaken within these eight sections to obtain sub-sections and sub-components. For instance, within the powertrain section, six sub-sections can be found including engine, intake system, exhaust system, fuel system, cooling system and lubrication system. This decomposition can be done step by step and finally a tree structure of the product can be obtained. With this tree structure, the information and knowledge used and generated throughout a project can be attached to different branches of this tree structure. As the amount of design information used and generated normally large whilst being related to various processes, the information about a particular component should be further divided into several stages for effective reuse. In this case, six main aspects are considered in Product model to classify design information, namely requirement & specification, product design & development, analysis & simulation, manufacture, testing and maintenance, as shown in the outer circle in Figure 5.3. Specifically, the information related to requirements & specification includes customer needs, regulations, standards, and the subsequent formal product design specification. Product design & development mainly covers information generated during the conceptual design and embodiment design processes, and thus involves idea generation, sketches, engineering drawing, 3D CAD models, materials selections and decision-makings. At the detail design stage, a range of analysis tasks, calculations and simulations are undertaken, and the information generated through these processes can be classified into a same category, i.e. analysis & simulation. The information about the manufacture and testing processes can be classified into two categories respectively. At the product's in-service stage, the information generated is mainly on service and maintenance of the product, which should be organised in a separate section. In this way, all the useful information regarding the product can be well structured and organised into six aspects and linked to specific sections and sub-sections.

### 5.2.3 Process model

The Process model is developed based on the classic engineering design process which is clear and well-structured. It identifies the information flow within an engineering design project, as shown in Figure 5.4. The information flow exists in four main stages, i.e. requirement analysis, design & development, manufacture & testing, and sale & service.

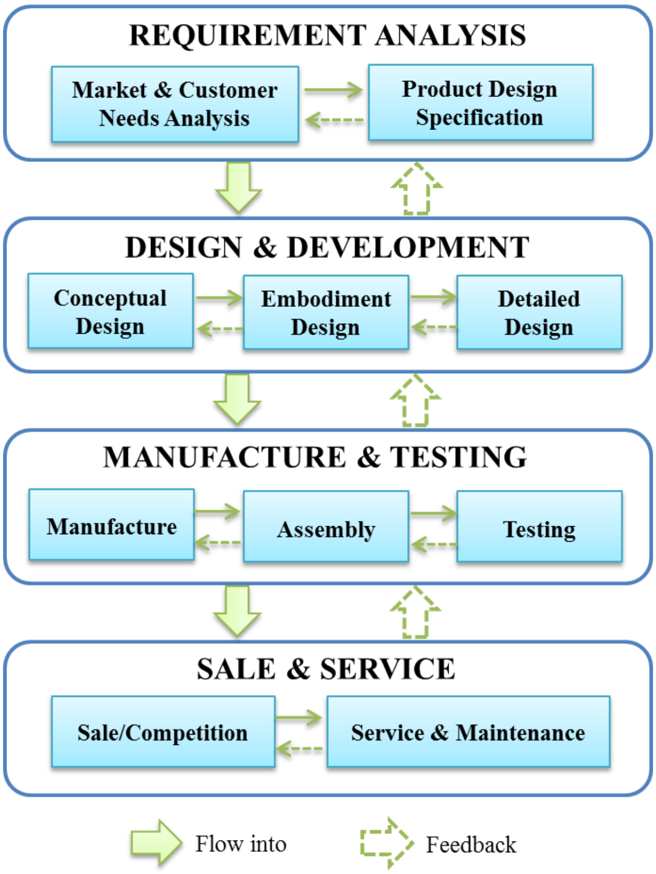


Figure 5.4. Information flow within an engineering design project by process model

At the beginning of an engineering design project, information flows into the project in a form of market and customer needs, along with several regulations and standards. Based on these kinds of information, the project proceeds to its design & development stage during which conceptual design, embodiment design and detailed design will be undertaken. Within this stage, a large amount of information concerning the design objects and processes will be generated. Specifically, information carriers include: (1) sketches, engineering drawings, and 3D CAD models; (2) analysis, calculation, and simulation results; (3) problem solving, decision-making and evaluation results. These types of information will flow through this stage and lead to the generation of detailed designs which will then flow into next main stage for manufacturing and testing. When the detailed design information is applied in the manufacture & testing stage, some of the new information will be generated and sent back to previous stages as feedback for evaluation and adjustment. Also, information related to manufacturing methods and testing results are also generated, which may be useful for future reuse and should be well organised. After the product is manufactured and launched to market, the information generated will be mainly related to sales and service. During the sales & service stage, the information from previous stages may be used, and new information may also be generated through maintenance and modification of the previous information. Overall, the Process model clarifies and streamlines the information flow within the whole process of an engineering design project, which can help the engineers to access the required information relative to specific stages. Also, the Process model provides a way of integrating the information from different individual working spaces of engineers according to the six aspects of information classification from Product model, which in turn allows engineers to track their current statuses of working within the whole project. In this case, the Process model is beneficial for the collaboration between engineers through providing a platform to track other engineers' current statues.

### 5.2.4 Project model

The Project model considers the key aspects for capturing and organising the supporting information in the project. These types of information are considered in terms of project management, and can be classified into 9 main categories namely market & customer needs analysis, stakeholder management, sponsorship & contract management, project planning & control, budget & cost control, purchase & warehouse management, quality control, risk & reliability control, and sustainability analysis, as shown in Figure 5.5.

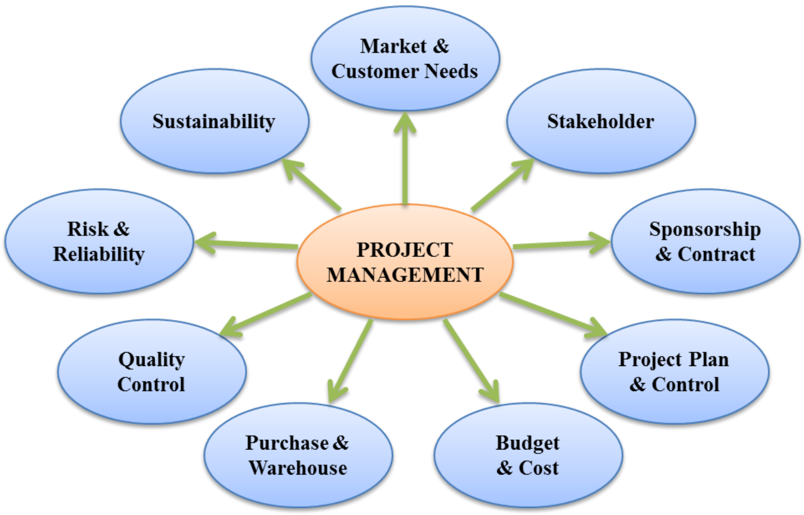


Figure 5.5. Organising supporting information in an engineering design project by using the project model

These types of information are separated from the information considered by Product model, as they are not used directly for product design and manufacture; they identify the scope and limitation of the project. Besides, these kinds of information may not be generated by engineers; they can come from customer needs analysts, project managers, accountants and salesmen. In the environment of collaborative working, the function of the Project model is to manage these kinds of supporting information and enable engineers to access to them efficiently when they require the relevant information for product design and manufacture.

### 5.2.4 Integration and application

The P3 framework is an integration of the Product, Process and Project models. These three sub models play different roles in capturing and organising various types of information within a project. Specifically, Product model organises the information on product design, manufacture and maintenance; Project model considers all the supporting information to the product; and Process model identifies information flow within the whole project. The integration of these three sub models is based on how they work together to build a systematic framework for combining and organising all the useful information generated during an engineering design project, as shown in Figure 5.6. This framework actually provides a hierarchical structure for the knowledge embedded in a range of design information whilst capturing the relationships between various kinds of knowledge. Besides, the information granularity of design knowledge can be controlled by selecting different levels of knowledge within this tree structure.

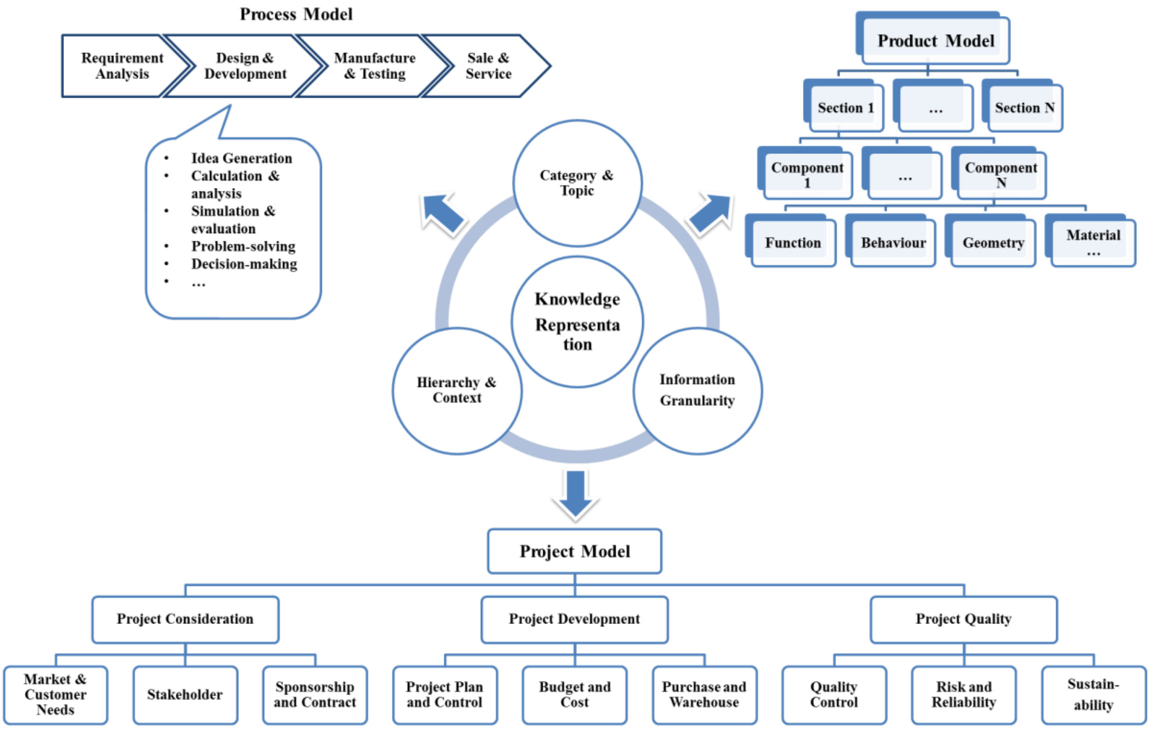


Figure 5.6. Integration of the Product, Process and Project models.

For instance, within the Formula Student racing design project, the Process model is firstly used to identify the whole process of the project according to the information flow, from requirement analysis, to design & development, then to manufacture & testing, and finally to maintenance and competition. The Process model can be regarded as building a trunk of the P3 framework. Then, for a specific stage, the Product model is used to organise the details of design information. As design information generated by each section or component of the racing car flows through the same process identified by the Process model, the Product model can be treated as building the branches for the trunk of the framework. Besides, the Project model which is focused organising all the supporting information will provide nourishment to the Process model and Product model which is similar to the water for the tree. This integrated framework finally builds a systematic structure which provides the context for capturing and representing knowledge.

Moreover, the systematic framework constructed by the P3 model is beneficial for providing user-centred way of capturing design knowledge. With a clear tree structure, design engineers can quickly locate the section they are working on. Then, they can capture and record useful information and knowledge in their individual working spaces, which can be linked together based on the Process model. Within the collaborative working environment, P3 framework provides a platform to combine the information of people from different disciplines, e.g. design engineers, manufacture engineers, maintenance engineers, analysts, managers, salesmen, etc. In this case, this platform helps them to share and reuse the information and knowledge more efficiently and effectively.

From the above discussion, the P3 model builds a systematic framework for capturing and organising design information generated during an engineering design project. The reason for building this framework is not only for organising the information but also for creating a structure with rich design context for capturing important design knowledge and experience by engineers. The design knowledge and experience of engineers is important intelligent properties which should be better recorded and shared. As it usually reside in engineers' brains, this kind of knowledge is difficult to capture and record for reuse. In order to capture this tacit knowledge, a rich context is required. In this case, the P3 model aims to provides a systematic framework which creates a design context to enable the capturing of useful design knowledge and experience from engineers' brains. These kinds of design knowledge and experience will be attached to the framework as leaves of a tree for better future reuse. The capture and representation of the design knowledge require a specific method which is the RFBSE model that will be described with details in the next section.

## 5.3 The Requirement-Function-Behaviour-Structure-Evolution Model

### 5.3.1 Overview

In order to effectively reuse design data, the design knowledge about what they are, how they are generated and why they are used in particular ways is significant as it identifies what kinds of data will be useful for reuse and how to understand and reuse them. During the engineering design process, the design knowledge generated by engineers includes both formal and tacit knowledge. Formal design knowledge is mainly embedded in several types of data, e.g. sketches, diagrams, CAD models, calculations, simulations, standards etc. (Owen & Horváth, 2002), while tacit knowledge mainly exists in designers' minds which is also referred as their experience. Tacit design knowledge is important as it contains useful engineering know-what, know-how and know-why behind reasoning processes and decision-makings. As formal knowledge is more standardised, it is relatively accessible and easier to be stored and managed. However, tacit knowledge is usually related to personal experience and thus is more difficult to capture and share. The solution for this is to develop a method which can guide the engineers to record down their design knowledge and organise it in a systematic and structured way for future reuse. Also, based on such a method, a computer tool can be designed and developed to support the knowledge capture and reuse process.

To provide this solution, a Requirement-Function-Behaviour-Structure-Evolution (RFBSE) knowledge representation model is proposed and developed in this research, as shown in Figure 5.7, for capturing and organising useful design information and knowledge.

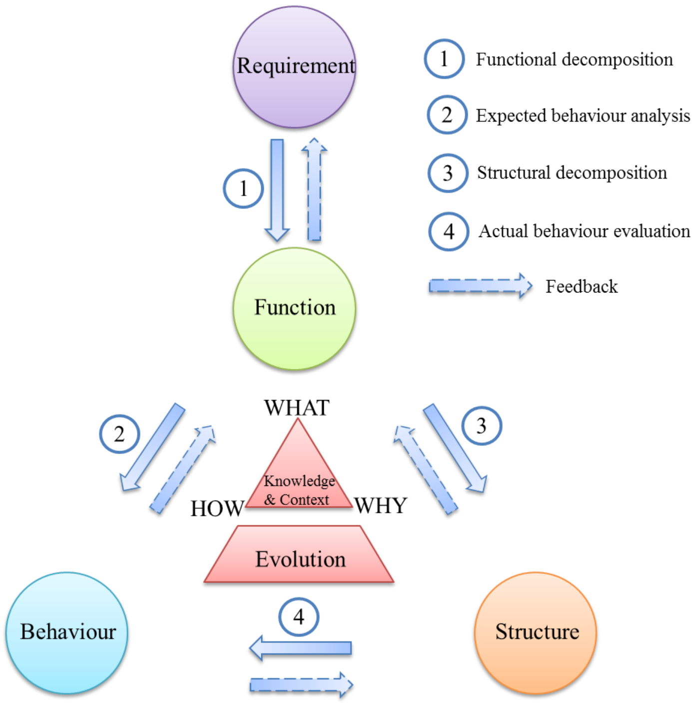


Figure 5.7. RFBSE model, a knowledge representation model

This model adopts the three main elements of the classic FBS ontology (Gero, 1990), i.e. function, behaviour and structure, and further emphasises the importance of requirement management and design evolution. Besides, the model provides a method for capturing tacit design knowledge through classifying them into know-what, know-how and know-why, and then integrating them with formal design knowledge to describe a complete piece of design knowledge. Moreover, this model provides a new way to undertake knowledge management as design project proceeds, which in turn can support the design process as undertaking the knowledge management. Also, the method that captures designs knowledge and experience within a clarified design context can integrate formal knowledge and tacit knowledge together for effective reuse. With its functionalities, the model can be used as the fundamental guidance in developing the next-generation knowledge management systems which can capture useful design knowledge and experience. Overall, this RFBSE model includes five key elements as indicated by its name, provides a method of classifying and capturing tacit design knowledge through know-what, know-how, and know-why, and enables the integration of tacit knowledge with formal design knowledge in specific design contexts. These will be described in detail in the following sections.

## 5.3.2 Capturing an integrated knowledge space

### 5.3.2.1 Requirement management

With today's trend in customer-oriented design and customisation, the analysis of customers' requirements becomes more significant and has great influence on the subsequent design stages. Development time, product quality and customer value can also be improved by effective requirements management (Baxter et al., 2008). In this case, requirement is regarded as an important independent element in the RFBSE model. As the first element considered in the model, 'requirement' has importance in determining the direction of the following elements. Within the design of an artefact or a component, requirement sets the boundary of the design space. Thus, in terms of knowledge management, the requirement management should also be undertaken in the first place. The information and knowledge needed to be captured in this case is focused on the factors limiting how the product can be designed, such as its working conditions, technical parameters, certain standards to meet, etc. By identifying these requirements, a boundary of the design space can be set. Also, effectively organising the knowledge on requirement analysis will be beneficial for exploring specific functions to meet the requirements raised. In other words, there is a causal connection between requirement and function, and managing this relationship effectively is important for the overall design process as the product is designed to meet certain requirements eventually.

### 5.3.2.2 Design objects deliberation and generation process

Function, behaviour and structure are the most important elements in describing design objects, which they have been analysed in many previous studies in the past three decades. The proposed RFBSE model also uses these three elements to describe design objects. In the early design stages of an artefact or a component, its ‘function’ is used to describe what it is going to perform and is generally obtained to meet certain requirements. In general, an overall function can further be decomposed into several sub-functions. This functional decomposition process involves considerable reasoning and decision-making to identify functional carriers for meeting specific requirements, which relies on various strategies used by different engineers. In this case, designers’ knowledge about how to undertake this decomposition process together with the main reasons behind key decisions should be captured so that the engineers who want to reuse the design can understand how the decomposition is approached, what issues are considered as well as why the particular functions have been chosen and elaborated.

The ‘behaviour’ of an artefact can be regarded as its status of performing functions and in this scene it can be described by several status parameters. According to the function and sub-functions that are supposed to be performed by the artefact, the expected behaviours can be derived using a number of ways including theoretical analysis, calculation, simulation, etc. In terms of the status parameters, the expected behaviours can be described using their preferred values or states. These expected behaviours show what the final product should perform, and indicate what should be achieved through design synthesis optimally. When a preliminary design is created, the actual behaviours can be assessed by comparing the values and states of certain status parameters to preferred values and states, i.e. those derived in the analysis of expected behaviours. A large amount of design knowledge and experience is generated during the analysis and assessment of behaviours, which can be mainly classified into two aspects. The first one is on how to obtain expected behaviours based on the functions and sub-functions. The second one is about the evaluation and improvement of actual behaviours, how to improve them so that they are close to the expected behaviours as much as possible, and more importantly why particular issues need to be considered.

Apart from the function and behaviour element, the structure element is also an important part of the RFBSE model. The most straightforward way of decomposing an artefact or component is through identifying its physical structure. This structural decomposition can divide the artefact or component into smaller parts to allow a more convenient and efficient management of its design data, information and knowledge. This structural decomposition is similar to the method proposed by the Product model in Section 5.2.2. However, the structure element proposed in the RFBSE model is not simply a structural decomposition as it also combines a method for building a detailed design context for the design knowledge to be captured. Also, this structural decomposition process should refer to the specific functions that the component or sub-components need to implement. In this way, the relationships between the abstract functional requirements and the functional carriers can be captured, which are beneficial for effective design reuse.

The RFBSE model can thus provide useful support for the design process through these three key elements, as they help establish the linkage between fundamental design information about an artefact or a component as well as the procedure of generating and processing this information. Based on these three fundamental elements, four important tasks relative to these elements have been highlighted, i.e. functional decomposition, expected behaviour analysis, structural decomposition, and actual behaviour evaluation. Among these four tasks, the useful knowledge and experience on how to approach a design problem and why to take particular actions is generated, which should be captured and organised for future reuse. As such, the RFBSE model can support the design process by addressing both design objects and design process and more importantly by capturing the useful design knowledge about problem solving strategies and specific issues that need to be considered.

#### 5.3.2.3 Design evolution

The fifth element of the model is the ‘evolution’ that refers to the design changes and improvements made during the design process. It explains how useful the knowledge and experience is as well as how to interpret design information and knowledge effectively for decision making. Design evolution is not simply design iteration in the sense that the latter is focused on modifying a design step by step through evaluating how well predefined targets have been met. However, design evolution is an evolving process whereby different versions of a design are delivered with consideration of more issues related to fundamental reasons behind the changes that need to be made. In other words, design evolution has a broader view and involves more information and knowledge. It includes the design iteration within one stage of the design, also the change from one version of the design to the next version, as shown in Figure 5.8.

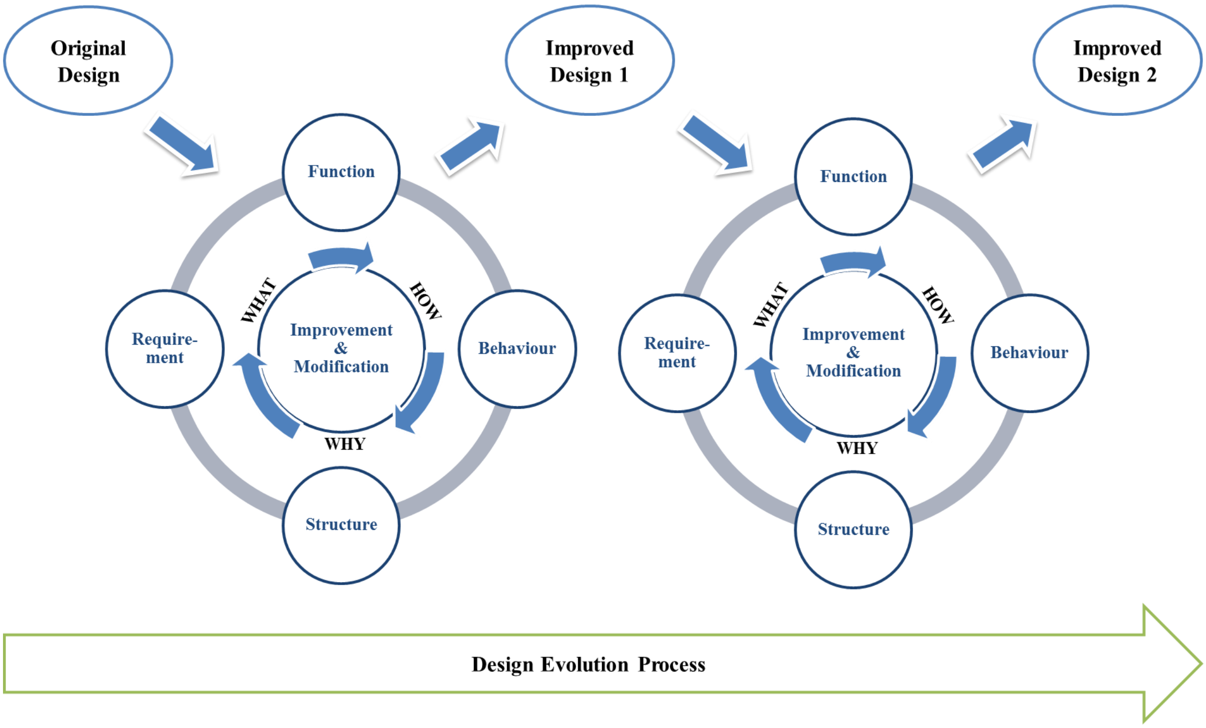


Figure 5.8. The evolution platform for gathering design information and knowledge

During design evolution, a range of changes and improvements on the design will be undertaken. Behind these changes and improvements, there are a range of factors, causes and efforts have been considered. Thus, the design knowledge and experience useful for future reuse is more likely generated during these processes and covers a wider range of topics. As the changes and improvements will affect the product structures and behaviours (in some cases even the product functions and its requirements), the design evolution process is enormous in combining the data, information and knowledge. In this case, a platform specific for organising the evolution process is proposed by the RFBSE model to manage this process and more importantly capture and reuse the design knowledge generated within the process. This platform combines all the design knowledge related to design evolution and can link the other four elements together to provide a use context of the knowledge for the effective reuse.

#### 5.3.2.4 Engineering know-what, know-how and know-why

Apart from the five key elements mentioned above, the RFBSE model also considers how to integrate tacit knowledge with formal knowledge. Essentially, this model adds more details to the bottom of the systematic tree structure for knowledge categorisation built by the P3 framework. For the RFBSE model, a diagram-based representation is used for capturing descriptive knowledge contents as well as the relationships between different pieces of knowledge. In this way, tacit knowledge can be integrated with formal design knowledge by linking the nodes within the diagram to external formal knowledge elements such as equations, engineering drawings, CAD models, data tables, etc. In terms of the contents of tacit knowledge, they are recorded using textual description and explanation in the form of a novel integration of engineering know-what, know-how and know-why. Specifically, engineering know-what refers to the knowledge for describing and explaining an engineering topic such as a material, technique, physical property, etc.; engineering know-how refers to the knowledge for approaching a problem by elaborating a solution path as well as by identifying, arranging and addressing the issues to be considered; and engineering know-why is the deep knowledge for explaining the reasoning process behind decision which concentres on why a certain phenomenon exits or why a particular action is taken to achieve a particular objective. Each type of description aims to capture detail granularity of knowledge, and can be integrated flexibly to describe a complex piece of knowledge. For instance, when capturing design knowledge, know-how is generally created using a number of nodes that linked to know-what nodes for describing objects as well as relationships, and know-why nodes for further explanation, as shown in Figure 5.9. With the combination of these three types of description, a complete piece of design knowledge can be captured and recorded. In this way, tacit knowledge can be structured and integrated with formal knowledge for describing the decision-making and reasoning process through the four main design tasks.

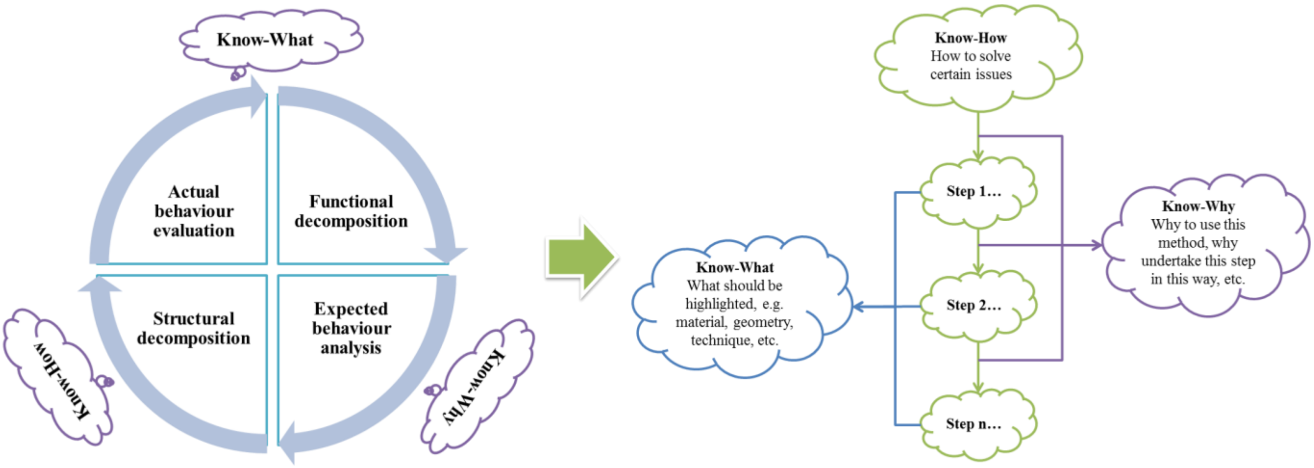


Figure 5.9. Using know-what, know-how and know-why to describe tacit design knowledge

### 5.3.2.5 Knowledge and context

There are two main functions of design context, one is for human users and another one is for computer support tools. For the former, design context depicts the background information of the design task, i.e. context of working, identifying which process is undertaking, what kind of problem is solving, what parameters should be considered, etc. This can increase designers' understanding in both knowledge capture and reuse. For the later, a clear design context is required in order to retrieve design knowledge to support designers' tasks, as the design context helps to locate relevant information. For instance, the intelligent recommendations which can be provided by computer tools during the collaborative designing process are highly dependent on design context. Thus, design context is an import factor that determines effective design reuse as it helps locate the useful information and on this basis facilitate the knowledge understanding and reuse.

The RFBSE model tries to capture the design context alongside useful information and knowledge captured by addressing two aspects, as shown in Figure 5.10.

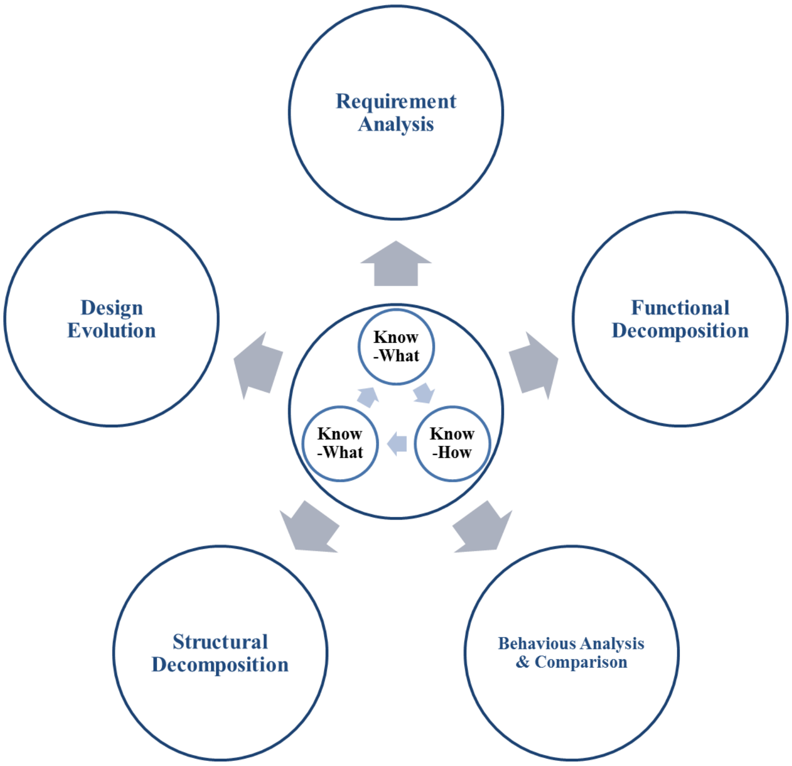


Figure 5.10. Capturing design context for relevant information and knowledge

Specifically, one is the systematic tree structure built by the model and another one is to use the tacit knowledge captured by know-what, know-how and know-why. The tree structure can be created in various area, including requirement analysis, functional decomposition, behaviour comparison and analysis, structural decomposition, and design evolution. These specified tree structures combine the required background information in order to capture the design knowledge behind the scene, which is actually proving the context of the design knowledge. Moreover, the relationship created by the tree structure helps to locate the knowledge captured. In this case, effective retrieval and intelligent recommendation on specific design information and knowledge can be achieved through exploiting specified contexts. On the other hand, the knowledge captured in the form of know-what, know-how, know-why provides three symbols on what kinds of knowledge they are, which is beneficial to identify their usage. In other words, the knowledge and experience itself provides useful design context by integrating different pieces of information and making the relationships between them more explicit.

### 5.3.3 Application of the model

The RFBSE model is proposed to help engineers capture their knowledge and experience through the design process, thus the key issues in the model's application are on how to give the engineers a clear clue in structuring and recording down the design knowledge and experience alongside the design process. The expression of the model has been shown in Figure 5.7, which clearly shows the key elements and design tasks that will be used for the knowledge capture and reuse. The model actually provides a way of guiding engineers where the design knowledge likely exists and how to capture it for reuse. Within a design process, designers firstly need to think about what kinds of requirements the design is going to meet. Then the concentration moves to the design objects itself by considering its function, behaviour and structure. Next, the focus comes to how to improve the design. This procedure has been concluded into four main design tasks by the model, i.e. functional decomposition, expected behaviour analysis, structural decomposition and actual behaviour evaluation. In this case, design knowledge generated during the design process can be organised based on the issues addressed through undertaking the four specific tasks. In other words, these four elements are created to systematically structure design knowledge, which are described in detail in the following paragraphs respectively.

Functional analysis is a formalised way of describing customers' requirements and transforming them into detailed functions. In this case, the functional decomposition task includes transforming these requirements into an artefact's functions and then dividing the main functions into several sub functions. Thus, the knowledge generated in this task can be organised by linking what kinds of function can be used to meet certain requirements and why the functional decomposition has been undertake in the specific way, as shown in Figure 5.11.

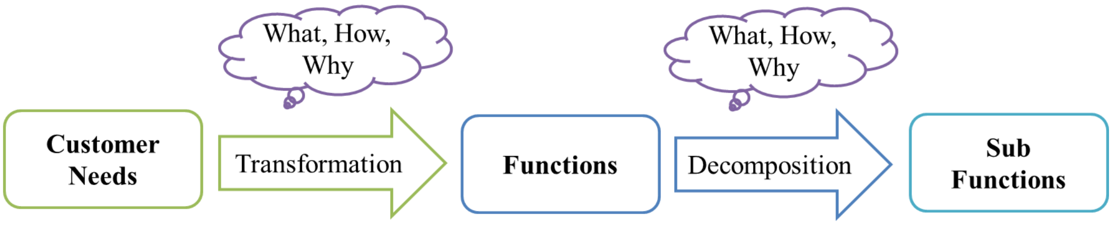


Figure 5.11. Knowledge exists on requirement analysis and functional decomposition

Customer needs are the most important input at the beginning of a design project, which indicate the goals and expectations of a product or service. Requirement analysis focuses on meeting the customer needs, which contains a range of valuable knowledge on how to meet the requirements. Besides, Product Design Specification (PDS) is created based on the analysis of these user requirements. How to transfer the requirements to a formal PDS and subsequently to the functions that need to be achieved to fulfil the requirements should be clarified. As customisation becomes more popular, design requirements can be diverse and sometimes conflict with each other, which mean that a large amount of tacit knowledge is involved within collective efforts of people with different roles such as design engineers, managers and marketing personnel. In this case, the knowledge about correlations between certain functions and the requirements they aim to address need to be identified and captured to provide guidance for the later design stages. In the RFBSE model, the requirement element is linked with specific function element to clarify this relationship and the identification of these relationships greatly relies upon designers' knowledge and experience.

Through requirement analysis, several functions are identified to meet the requirements, which can be subsequently decomposed into more detailed sub-functions. Then, the task of expected behaviour analysis will be undertaken to find out the key indicators for evaluating how the function and sub-functions can be implemented. This process includes several activities, such as idea generation and evaluation as well as a range of decision-makings. The knowledge generated at this stage mainly comes from the rationale behind design divergence and convergence, problem-solving, and decision-making. The knowledge generated within these processes is classified into Know-what, Know-how, and Know-why knowledge elements to describe the valuable design knowledge generated, as shown in Figure 5.12.

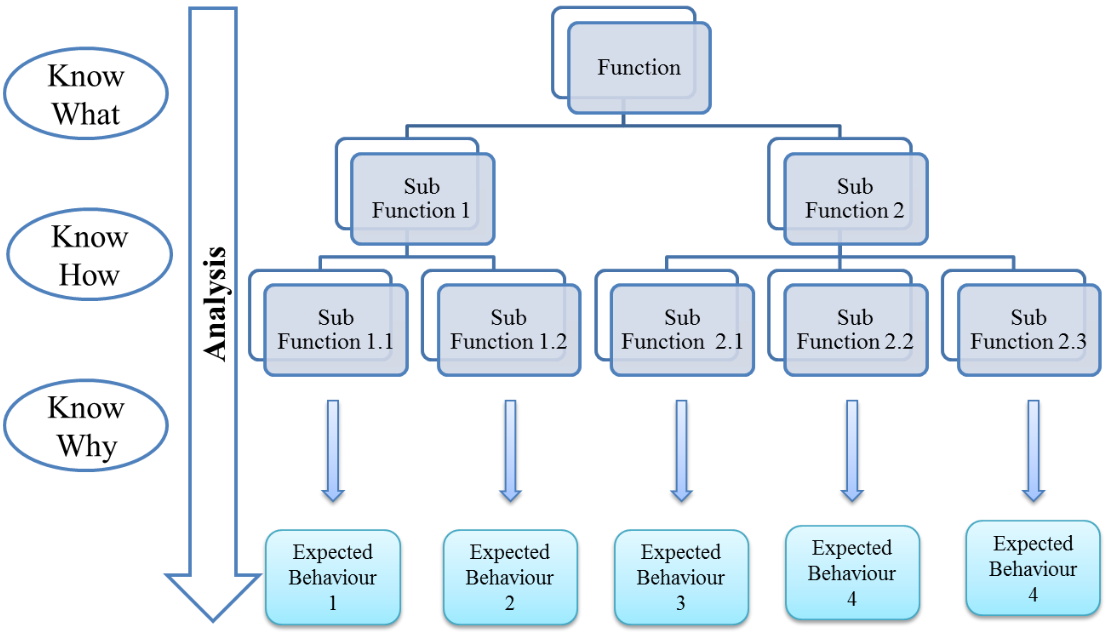


Figure 5.12. Functional decomposition and expected behaviour analysis

The expected behaviour analysis task is used to transform functions and sub-functions into the expected behaviours. Alongside the analysis, design synthesis is undertaken started to obtain necessary structure and form to realise the specific expected behaviour, as shown in Figure 5.13. In order to organise the design knowledge effectively and capture the specific context with it, a decomposition of the generated structure should also be undertaken. The structural decomposition provides a way to organises the information and knowledge related to each component and sub-component of an artefact systematically.

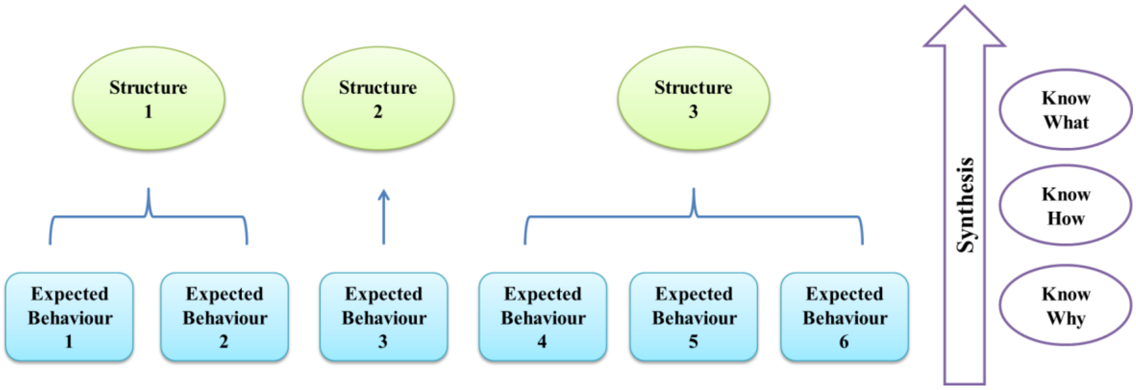


Figure 5.13. Design synthesis from expected behaviour to structure

When the structure of an artefact or a component is obtained through design synthesis, its actual behaviour can be determined. Then, this actual behaviour should be compared to the artefact's expected behaviour for evaluation and improvement. During this process, a range of modifications and improvements are made through considering particular issues, which is regarded as a design evolution process. Within this design evolution, a range of design knowledge will be generated especially the tacit knowledge. This tacit knowledge is related to decision-making, problem solving and design argumentation, which requires a specific method to link different pieces of information together. The method provided by the RFBSE model is to track each status of the artefact, based on an analysis of its actual behaviour after changes, as shown in Figure 5.14.

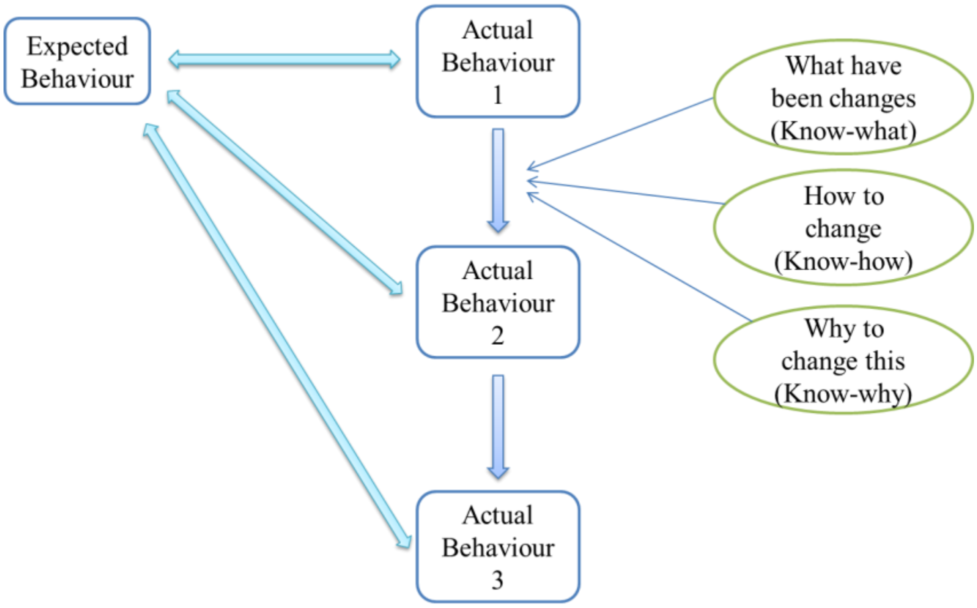


Figure 5.14. Capturing design knowledge through evaluating actual behaviour with expected behaviour

From a status improved to the next one, e.g. actual behaviour 1 to actual behaviour 2, the design knowledge generated in this process can be organised into what have been changed (know-what), how to change it (know-how) and why to change this (know-why). Also, based on this procedure, the modifications and improvements on an artefact or a component can be tracked. As this procedure provides a context for relevant design data and information generated and used, it can improve the efficiency of locating the useful design information and knowledge when reusing the previous designs.

## 5.4 Discussion

In modern product development, most artefacts are produced based on existing designs, and as such capturing the knowledge and experience of how to improve existing designs is certainly essential in this case. The pattern proposed in the RFBSE model that tracks the evolving process of a design is an effective way to integrate relevant information and knowledge of the design. This kind of knowledge mainly relates to an artefact's behaviour and structure, supported by detailed analysis of related functions and requirements. Thus, the evolution element can link these four elements of the model together, providing a useful context for the design knowledge captured.

One purpose of the RFBSE model is to capture useful tacit design knowledge and integrate it with formal design knowledge through a systematic framework for efficient reuse. This is achieved by firstly building a systematic framework for organising and categorising relevant design information. Then useful design knowledge can be organised within such a framework, including both formal and tacit knowledge. For tacit knowledge, it is described using several knowledge elements, namely know-what, know-how, and know-why. These three elements are incorporated in a novel diagram-based representation which enables tacit knowledge to be captured using a highly structured form with concise but meaningful contents.

Referring to the relationship between the P3 framework and the RFBSE model, they are proposed to work together for structuring and capturing design information and knowledge, while focusing on different levels. The P3 model builds a systematic framework to organise the useful information within a complex collaborative working environment, which creates a design context for capturing design knowledge. Based on this design context, the RFBSE concentrates on identifying where the useful design knowledge will be generated and how to capture and organise it for reuse. Therefore, P3 framework and RFBSE model have specific tasks, while they can work together for the effective knowledge management and reuse. They are the core of the knowledge management system designed and developed in this research.

## 5.5 Summary

It has been identified that effective and efficient management of design knowledge has significant impact on the success of a product. This research proposes a Product-Process-Project framework to clarify the major elements, activities and issues in an engineering design project and indicates the way for structuring them for efficient reuse. There are three sub models of the framework, namely the Product, Process and Project models. These three models are integrated to organise the information within a collaborative working environment and further create a context for capturing and representing design knowledge. Moreover, this P3 model emphasises a user-centred concept which can be used to guide how to build individual working spaces for engineers in knowledge management systems.

Additionally, this research proposes a RFBSE knowledge representation model which aims to capture design knowledge through the design process for reuse. The model has five key elements, i.e. requirement, function, behaviour, structure, and evolution. Among them, the function, behaviour, and structure elements are the backbone for describing design objects and design process. The requirement element considers requirement analysis whilst the evolution element is used to track the design changes and improvements. With these five elements, the RFBSE model has identified four main design tasks in which a lot of useful design knowledge is generated. This model helps capture valuable tacit knowledge that is only possessed by individual designers in the activities of analysis, synthesis, evaluation, etc. Also, it can integrate the tacit design knowledge with formal design knowledge embedded in CAD models, formulas, calculations, etc., through a novel diagram-based representation in a semi manual way. In summary, the P3 framework and the RFBSE model are proposed for understanding, categorising and representing design knowledge, laying the foundation for the development of new methodologies and tools for the next-generation of knowledge management systems.

# Chapter 6

# Design and Development of a Web-based Knowledge Management System

## 6.1 A Methodology for Capturing Integrated Design Knowledge

Undertaking knowledge management in an engineering design project can help engineers to meet their information and knowledge needs throughout the design process, reuse part of previous designs, and eventually improve design efficiency. This knowledge management task is usually assisted by computer support tools, i.e. knowledge management systems. Traditionally, there are several types of software systems that can undertake the knowledge management tasks to some extent, e.g. Product Data Management (PDM) system, Enterprise Resource Planning (ERP) System, Product Lifecycle Management (PLM) system, etc. These systems can organise and store product data and information, e.g. computer-aided-design (CAD) models, engineering drawings and relevant documents, and focus on capturing and maintaining information on products and/or services through its development and use life (Chandrasegaran et al., 2013). However, they cannot deal with the design knowledge and experience generated by engineers during the design process. This kind of knowledge differs from shallow knowledge that concerns facts and numbers, it explains the decision-making process and the design rationale associated with this process, e.g. why a component uses a particular structure, why a material is chosen for a part instead of others, how to process a component for effective manufacture, etc. With this kind of deep knowledge, previous design data and information can be reused more effectively and efficiently as rich design context is captured and supplied. Therefore, the new generation of knowledge management systems should move from data-centred solutions towards knowledge-centred solutions. To enable this move, a clear methodology is required to transform the theoretical models into practical steps as well as applying the state-of-the art information technologies for the implementation of the systems

This knowledge-centred system concept is an idea that focuses on important knowledge generated and exchanged between engineers and then organising the information and data related to the knowledge, which is based on the RFBSE knowledge representation model discussed in Chapter 5. In this case, the main tasks of such a knowledge-centred system are to create a virtual and collaborative environment to allow the capture, representation and reuse of knowledge by group of engineers. This environment emphasises capturing knowledge as a part of a design process and as such the P3 model can provide a useful systematic framework for organising and categorising design knowledge by placing it in an integrated context of product, process and project.

Therefore, the P3 framework can help organise the information within an engineering design project as well as providing the process and project contexts for design knowledge while the RFBSE model can be used to guide how to capture and represent the useful design knowledge and experience for future reuse.

A methodology has been obtained from this research to detail how to apply the knowledge models and the next-generation knowledge management system to capture and reuse integrated design knowledge, as shown in Figure 6.1. According to this methodology, the P3 framework is firstly create a systematic framework for the design knowledge to be captured, and then the RFBSE model is used for the key tasks of capturing useful design knowledge and experience. Based on these two models, the system architecture of a Web-based knowledge management system can be designed, which has three layers, i.e. user interface, core application and repository. Specifically, the main aspects of the P3 framework, namely creating systematic framework, connecting individual working space and supporting collaborative working, determines the broad architecture of the system. The key functionalities of the system which involves capturing, representing and reusing knowledge are implemented with the guidance of the RFBSE model. Based on this methodology, the system design and development can be undertaken, with the details demonstrated in the following sections.

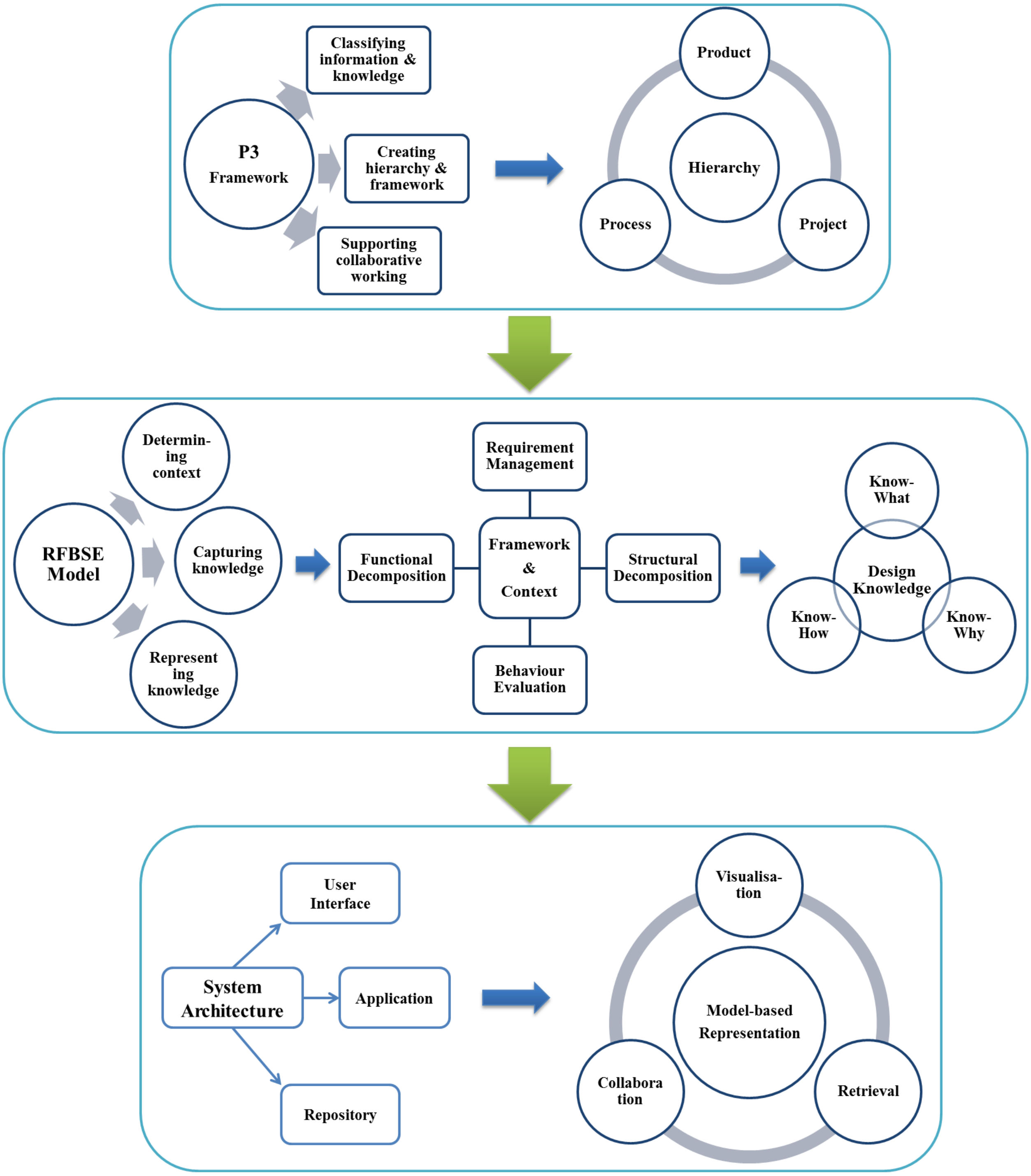


Figure 6.1.A methodology for capturing and reusing integrated design knowledge

# 6.2 System Design and Architecture

## 6.2.1 Overview

It is envisaged that the next-generation knowledge management systems focus on knowledge-centred solutions for organising data, information and knowledge in a collaborative working environment which supports a user-centred way of capturing and reusing knowledge. Specifically, there are three main characteristics of a next-generation knowledge management system for engineering design; (1) it can be used to capture and manage deep knowledge rather than simply to organise data and information; (2) it supports collaborative working environment which not only allows engineers to use the system in distributed working places but also allows them to capture and reuse knowledge as a design project is conducting instead of after it is completed; and (3) it should emphasise a user-centred solution for managing knowledge by exploiting designers' context of working to supply or request knowledge. Thus, the purpose of the design and development of the system is focused on achieving these three characters.

With the methodology proposed in Section 6.1, the architecture of the system has been designed and the enabling technologies for the system have been considered. Specifically, the system architecture can be divided into three layers, namely User Interface, Application, and Repository layers, as shown in Figure 6.2. To be adapted for a collaborative working environment, the system is to be developed as a Web-based solution. In this case, the user interface is built to be accessed using an Internet browser. Thus, a range of Web-based enabling technologies are used, including Hypertext Markup Language (HTML), JavaScript, Cascading Style Sheets (CSS), Professional

Hypertext Preprocessor (PHP) and Structured Query Language (SQL). The application layer is the core of the system, which involves the key functionality of capturing, representing and reusing knowledge. In order to effectively support the understanding and reusing of information and knowledge based on the user-centred concept, newly developed information technologies based on HTML5, jQuery and KineticJS are used to create the applications. The repository layer is the fundamental part of the system, storing the data, information and knowledge captured, which uses MySQL for the database management and PHP for the communication between the system and the database. Each layer will be described in details in the following sections.

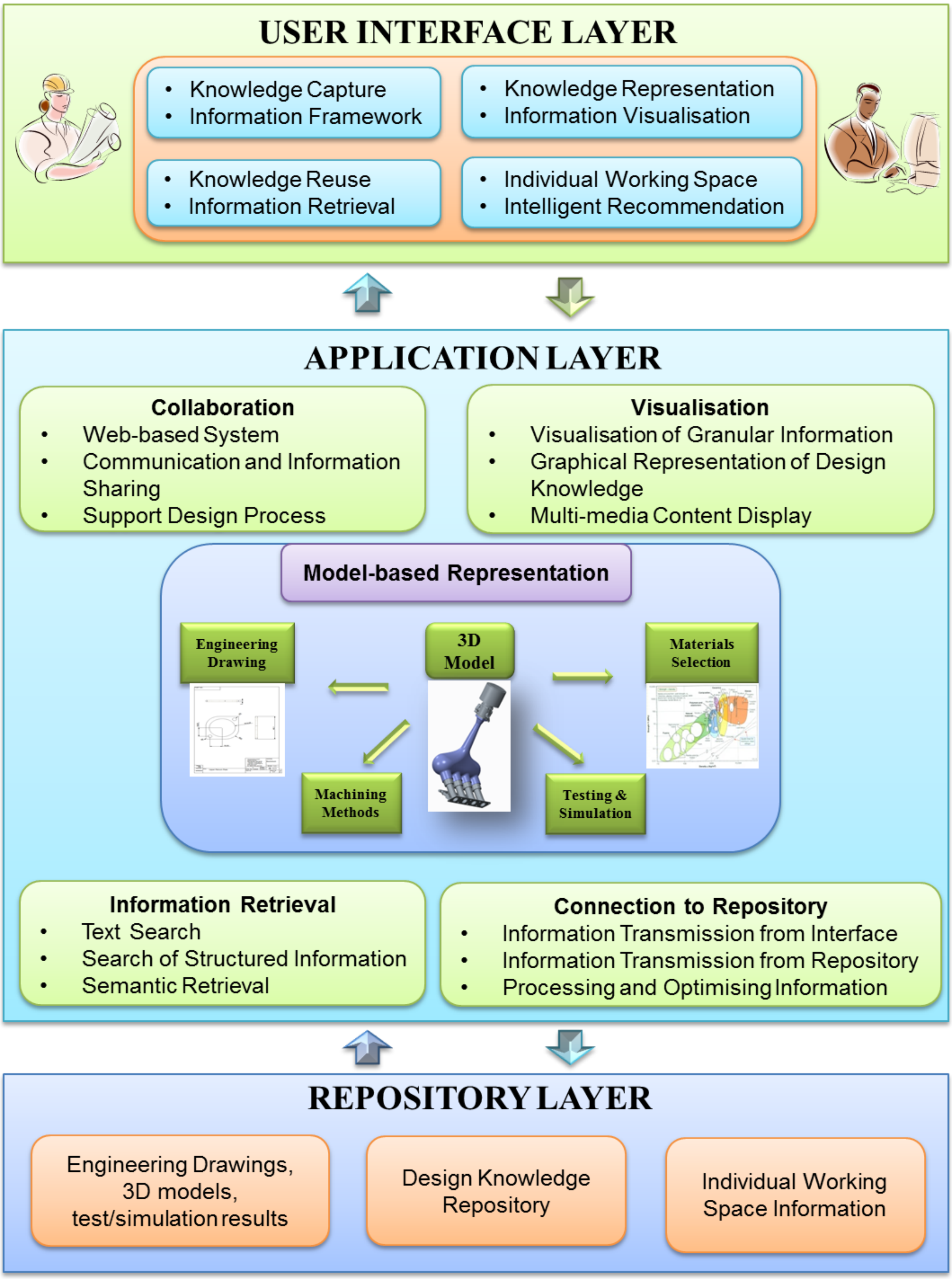


Figure 6.2. System architecture

### 6.2.2 User interface layer

Within today's global cooperation and distributed working environment, the Internet is highly relied upon and provides option for collaborative working in various locations. Additionally, Web-based computer tools have become the preference of design engineers as they are easily accessible, and thus the knowledge management system developed in this research uses this Web-based concept. In this way, the user interface of the Web-based knowledge management system can be accessed by using a Web browser from any location connected to the Internet.

The user interface has two main functions: determining the layout of the system and providing the platform for the users to use the various functions of the system. The layout of the system is based on its scope of managing design knowledge in an engineering design project. There are three main tasks to be supported by the user interface, namely, knowledge capture, knowledge representation and knowledge reuse. The interface should provide straightforward and effective ways of performing the relevant system functions for these tasks. Regarding to knowledge capture and representation, a Graphic User Interface (GUI) is provided to allow users to create information framework and record the useful information in a visualised way. A retrieval GUI is also provided for the functionality of connecting to database and search for desired information. Besides, the interface should also enable operations for conducting information retrieval and receiving/accessing information regarding to each engineer's individual working space. Moreover, several basic functionalities should be provided by the user interface, including login/logout, navigation, information recording, communication with database, etc. With the highly developed HTML5 Canvas technologies, graphic representation on Web browser becomes possible, and it is used in the system. At the same time, Asynchronous JavaScript and XML (AJAX) technology can be used to communicate with the database synchronously. Details of these functionalities are demonstrated in the later system development section.

### 6.2.3 Application layer

The application layer involves the components for implementing the main functions of the system as well as the main enabling technologies for their implementation. Among several functions, the model-based knowledge representation is the core. The representation aims to integrate the design space and the knowledge space. Within the knowledge capture GUI, engineers can record and organise their design information in a tree structure, according to the guidance from the RFBSE model. Different pieces of design knowledge on know-what, know-how and know-why can be attached to this tree structure to explain the decision-making process and their associated design rationale for specific design information. Relevant data and information can also attached to the interface, e.g. 3D CAD models, engineering drawings and other relevant documents. Besides, the tree structure can be expanded to allow adding more details about specific artefact or component.

Based on the main functionality, the other four functions are proposed to be used as a support to ensure the main function is well implemented. Specifically, collaboration focuses on allowing the system to be used by multiply users synchronously, supporting communication and information sharing. Visualisation serves the purpose of enabling graphic information representation and operation, display of multimedia information and CAD models, etc. Information retrieval involves developing advanced retrieval algorithms for searching information, e.g. keyword-based text search, search of structured information, and semantic retrieval. Connection to repository deals with how to build a bridge between the user interface with the repository for effectively saving and using data and information.

In order to implement the functions of the system mentioned above, their enabling technologies are also considered. In the Web 2.0 age, HTML5, as an emerging technology, is becoming increasing popular in developing rich interfaces and powerful interactions on the Web environment. Also, it supports multimedia information displaying and processing for the webpage. Besides, using HTML5 can allow the system to operate in Web environment rather than installing package in the local computer, making the system easier to access. Therefore, it is chosen as the main technology that supports the applications proposed for the system. Based on HTML5' fundamental structure, Web programming language JavaScript will be used to undertake the detailed tasks with its useful supporting libraries like jQuery and KineticJS. Besides, a server scripting language PHP will be used to save and use data and information in the MySQL database. With the help of these Web programming languages and database, the applications proposed for the system can be developed and implemented.

### 6.2.4 Repository layer

The repository layer includes database, local data storage and Web space, in which the database section is the core part. The data, information and knowledge captured in the system are mainly saved in database. In order to achieve effective data management and retrieval, the database is designed to have a modular structure and can be divided into three parts: (1) engineering drawings, 3D CAD Models, test/simulation results and other relevant documents; (2) design information and knowledge, which is mainly textual but involves various elements as well as the links between them; and (3) individual working space information that involves the information generated and used by separate users and the information used to describe their contexts of working. This modular solution provides a clear structure which is beneficial for managing and storing design information and knowledge. Besides, the documents requiring large storage spaces can be stored in the local storage or Web space while only their addresses in these storage spaces are stored in the database for retrieval and use.

The MySQL database management system is used in this research due to its good compatibility with PHP. As the repository is the fundamental part of the system, it should be designed and developed alongside other applications. The tables for storing various types of data and information in MySQL are designed by considering the main functionality to be achieved in the application layer. Also, the database should allow extendibility which means that more columns and tables can be added in the future for new types of data and information. Overall, the repository should have the function of coordinating different kinds of information and support the display and retrieval of the information in the user interface.

## 6.3 Prototype System Development

The system architecture proposed above has identified the outline of the system and the key functions it needs to perform. Also, the main enabling technologies have been identified for each specific layer. The following sections will describe how the prototype system has been developed according to this architecture. First of all, the system layout on user interface is described. Then, the design and development of the key functionalities of the system, i.e. knowledge capture and representation, will be demonstrated using the idea of three engineering design stages from conceptual design to embodiment design and then to detailed design. Finally, the database design and development will be described in details.

### 6.3.1 User interfaces of the system

The system is developed and located in a server at the University of Portsmouth, and users can access is by using its Web address, kms.myweb.port.ac.uk, through any Web browsers. As a Web-based system, the main user interfaces are built in Web environment, and thus developed by creating a range of HTML, CSS and JavaScript files. Besides, there are two JavaScript libraries are used for effectively implementing system functions. The first one is an easy-to-use Application Programming Interface (API) named jQuery, which can make HTML document traversal and manipulation, event handling, animation, and AJAX much simpler. Another one is KineticJS, which is a fast, robust, HTML5 Canvas Library and mainly used for the graphic representation of the system.

Among several user interfaces, the one that every user should firstly access is the system login/register section, as shown in Figure 6.3. This interface can not only protect the security of the system, but also collect the users' information when they login or register in the system. Once a user goes to this section, he/she should enter username and password in order to access the system. Also, user should select a specific engineering design project for further operation, as through this way the data for different projects can be kept confidential and stored in different databases. For new users, they are required to register with personal information including name, username, password and email address. As the email address is set to be unique in the database, each email address can only be registered once. Figure 6.3 also shows that the RFBSE knowledge representation model is displayed in this section in order to remind the engineers the core method for capturing and organising their design knowledge and experience for reuse.

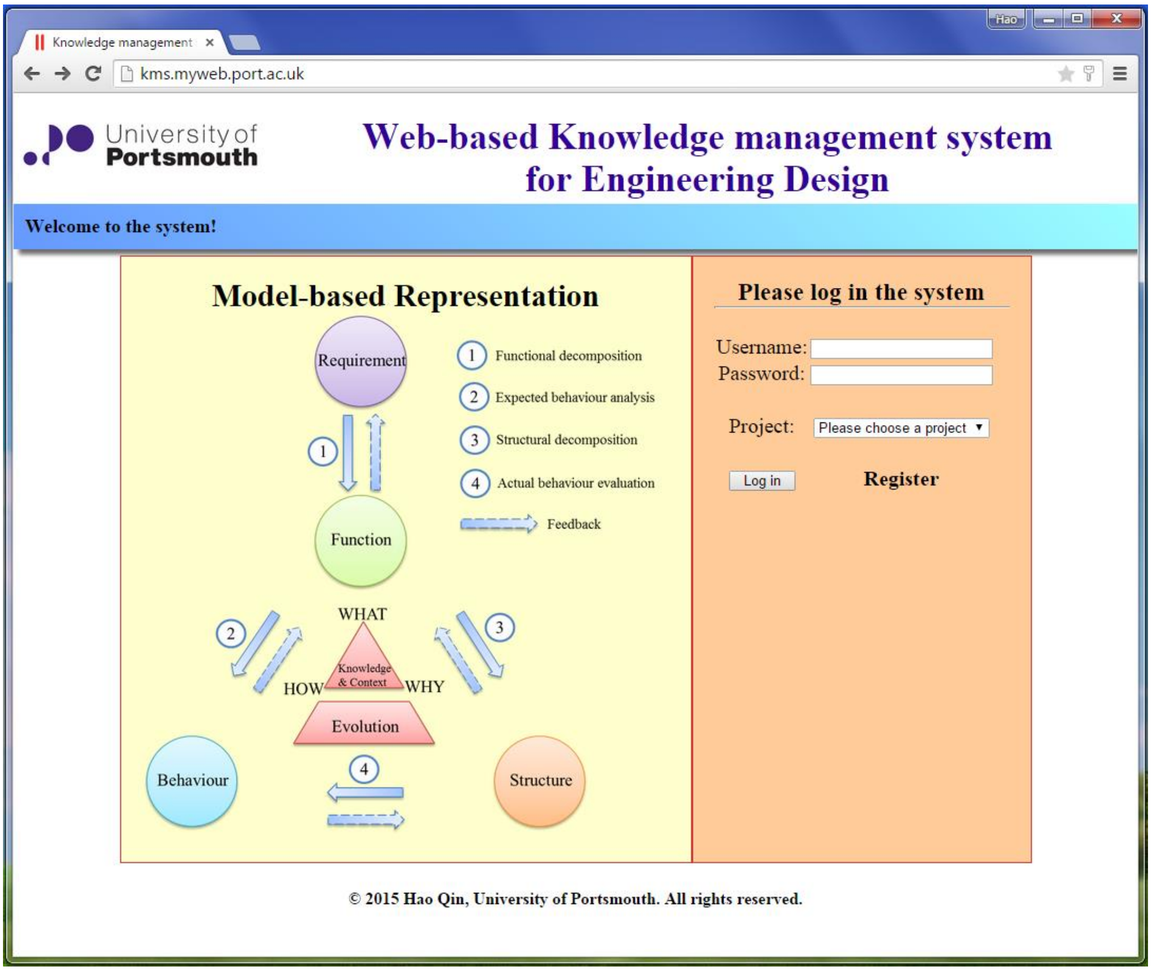


Figure 6.3. Login/Register section of the system

After user successfully login to the system, four options can be chosen from the navigation bar of the system, i.e. knowledge capture, knowledge retrieval, knowledge framework, individual working space. The knowledge capture option is the main functionality of the system, providing all sorts of operations on capturing and representing design information and knowledge for future reuse. Under this section, users can create a new knowledge capture project or edit existing project, as shown in Figure 6.4. For creating a new project, the title and description should be added to define the specific project. The RFBSE model is also displayed in this section with a brief description of the model listed on the right of the page. Also, a user instruction document is provided which can be opened in a new window through a hyperlink to provide the procedure of how to capture design knowledge using this interface step by step.

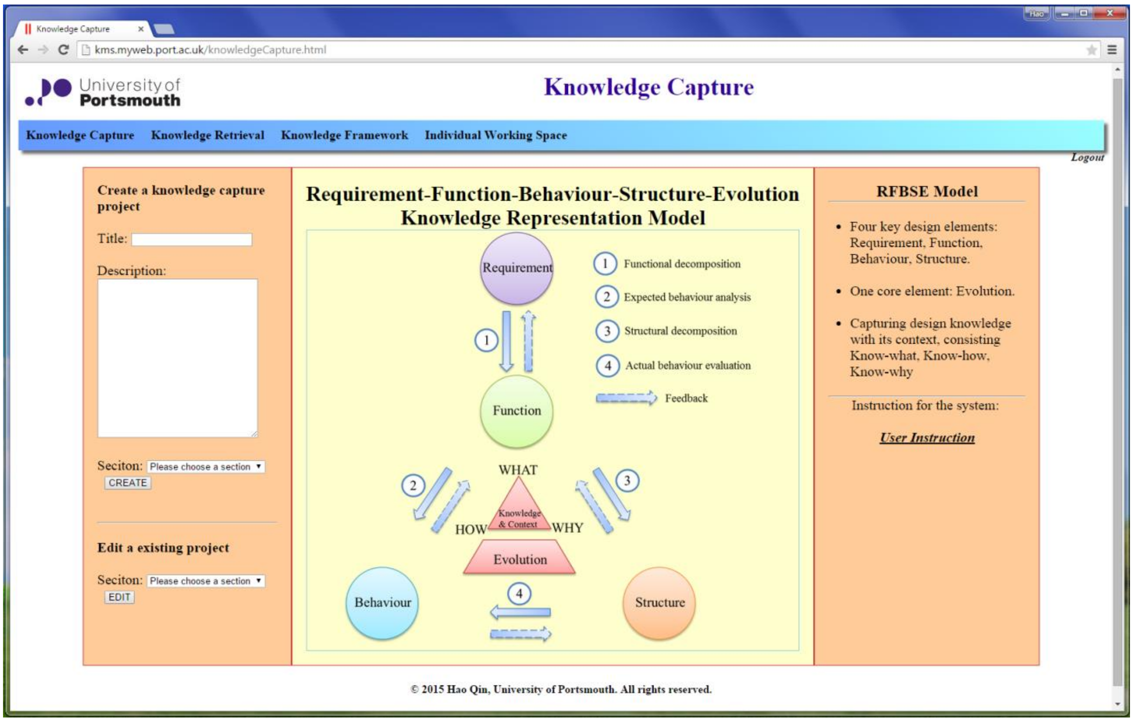


Figure 6.4. Knowledge capture function of the system

When the user created a new knowledge capture project or chose to edit an existing one, a new section will be opened for the detailed operations on the knowledge capture and representation, as shown in Figure 6.5. This is the knowledge capture GUI provided by the system, which is the key functionality of the system. The interface mainly has eight parts, with number 1 to 8 shown in Figure 6.5. Most of the functions in the knowledge capture GUI are operated on the left and right canvas. These two canvases are developed and supported by the HTML5 canvas technology, which enables the graphic representation on the webpages. The left canvas is used for displaying design models while the right canvas is used for capturing and representing design information and knowledge using a graphic representation. The operation option bar in the middle of these two canvases is used for editing the contents on the canvases. Within this interface, there is a navigation bar on the top left corner, which allows user to switch between different sections in the system. Also, there are two kinds of attachments can be inserted to the interface at the left bottom corner: one is used to insert and display design models on the left canvas while the other one is used to save the design data and documents related to the current interface into the database. Besides, in the bottom of the right canvas, there is an instruction toolkit which can provide instructions to users according to the operations they are working on.

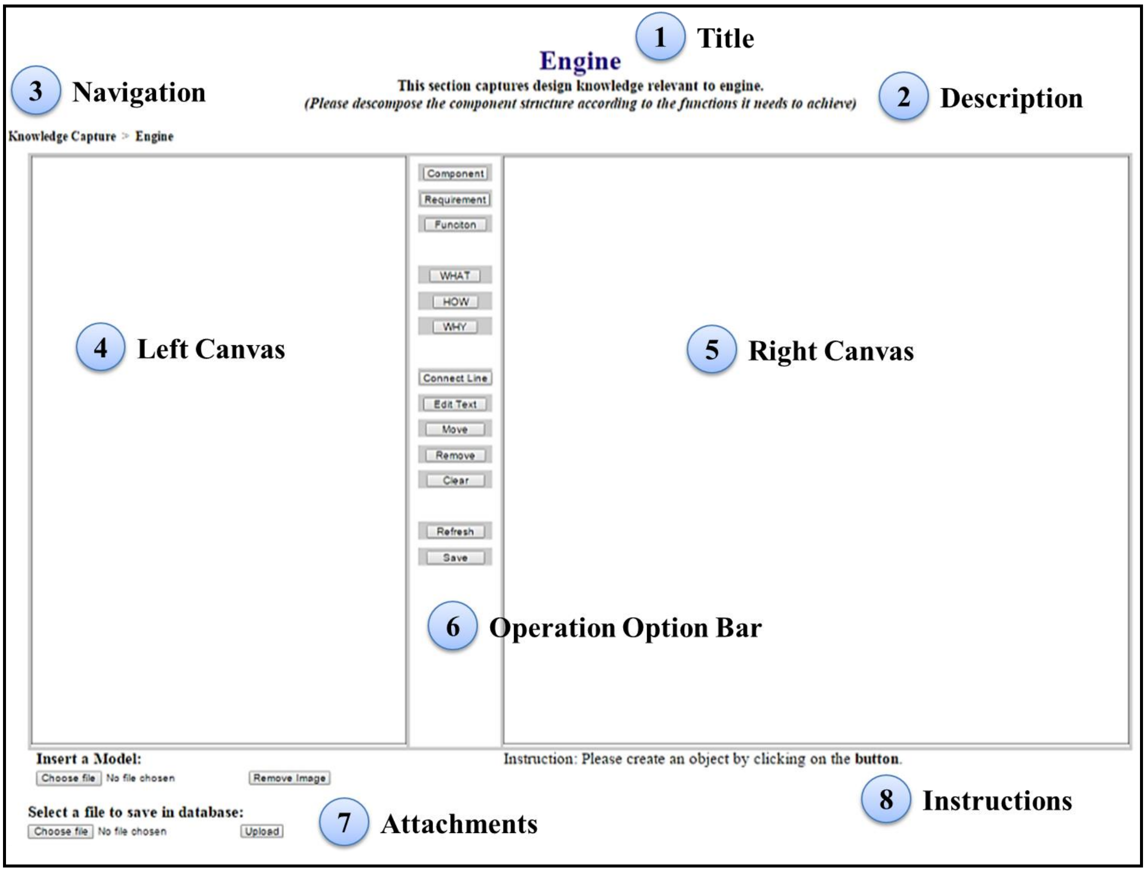


Figure 6.5. Canvas for capturing design knowledge using a graphic representation

Apart from the knowledge capture GUI, the system provides a knowledge framework GUI to organise all the information and knowledge captured by the knowledge capture GUI, as shown in Figure 6.6. It uses the P3 model to build a systematic framework to organise the information throughout the whole engineers design project, which can help users to access the specific section straightforwardly and efficiently. Specifically, the product section links to the specific sections of an artefact or a component; the process section is used to track the information through specific process; the project section provides the access to the data and information on project management; and the people section links to uses' individual working spaces.

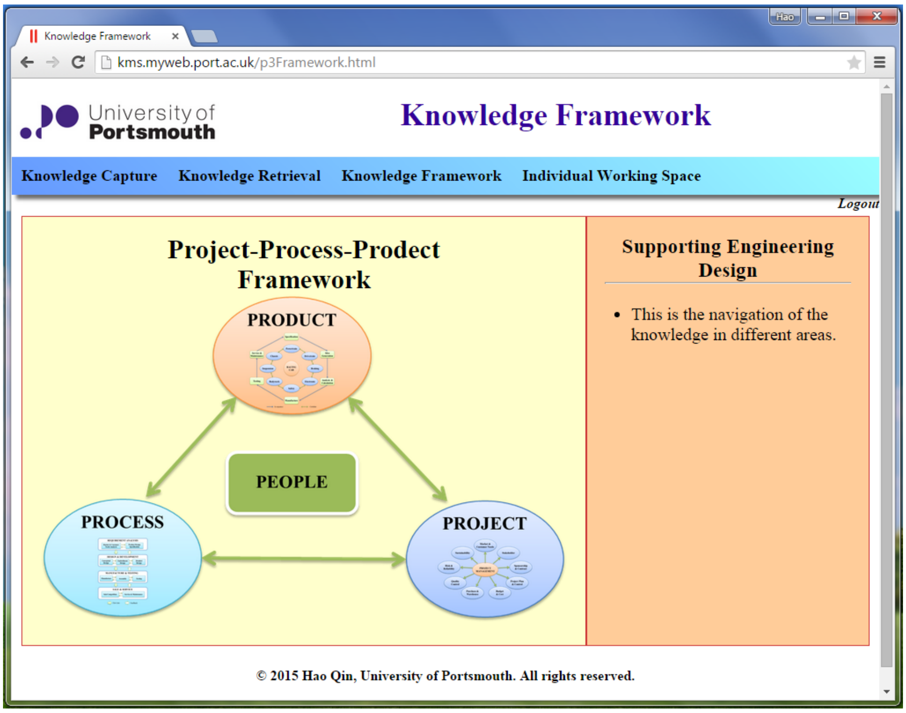


Figure 6.6. Structure project data and information by P3 model

Besides, the system has two supporting GUIs, namely knowledge retrieval and individual working space. The knowledge retrieval GUI is used to search required information from the database in a key word based method, while the individual working space is a GUI that helps engineers to organise and track their individual information.

## 6.3.2 Core system functions design and development

### 6.3.2.1 Conceptual design on the knowledge capture function

The core functionality of the system is to capture, represent and reuse design knowledge, and the model-based representation plays an important role in achieving this functionality. In order to perform this functionality, a knowledge capturing GUI is required, which is mentioned in last section. The design of this interface is based on the five elements in the RFBSE model, i.e. requirement, function, behaviour, structure and evolution, as well as the main design tasks considered in the model, i.e. functional decomposition, expected behaviour analysis, structural decomposition and actual behaviour analysis. The knowledge capture GUI aims to provide good support for engineers to capture design knowledge based on a framework created by these elements when they are undertaking the design tasks. In this case, two kinds of elements are required in the interface. The first one is engineering elements which include the five key elements in the RFBSE model and the other aspects usually considered in an engineering design project such as material, geometry, manufacture, etc. The second kind of element is reasoning elements that include know-what, know-how, and know-why, which is used to capture design knowledge and explain the decision-making process. The engineering elements are used to build a tree structure for organising the relevant design information of an artefact or component while the reasoning elements are the 'leaves' of the 'tree' and linked to its specific branches. As the knowledge is captured at the same time when the engineers are undertaking the design tasks, it is regarded as an integral part of the design process. In this way, design knowledge can be captured with rich design context so that it can be more easily found, understood and reused.

Further operation should be allowed on the engineering elements in order to add more details for explanation. For example, the evolution element is created to track design changes and improvements of an artefact and record the design knowledge behind the scene. In the interface, this engineering element can be created and linked the related artefact, and it can be double-clicked to open a new window where detail explanation can be added. Besides, in order to clarify the relationships between different elements, all the elements should be linked in a logical way using arrow lines. Through a one-way logic linkage, a systematic tree structure can be built for clearly organising design information and knowledge. Moreover, the design data related to the artefact, such as CAD models, engineering drawings, simulation results, etc., they should be attached to the interface and save into database in order to provide supplementary information.

#### 6.3.2.2 Embodiment design and algorithm

This section aims to explain in details on the functionalities of the knowledge capture GUI shown in Figure 6.5. Within this interface, design information and knowledge can be captured using graphical representation on the right canvas. Specifically, the engineering elements are used to build a tree structure (e.g. Component and Function element) and create a design context, while the reasoning elements are used to describe design knowledge (e.g. What, How and Why). There are other operating options related to the canvas, which includes editing the canvas and communicating with the database. All these options can be activated by the buttons on the side of the canvas, as shown in Figure 6.7.

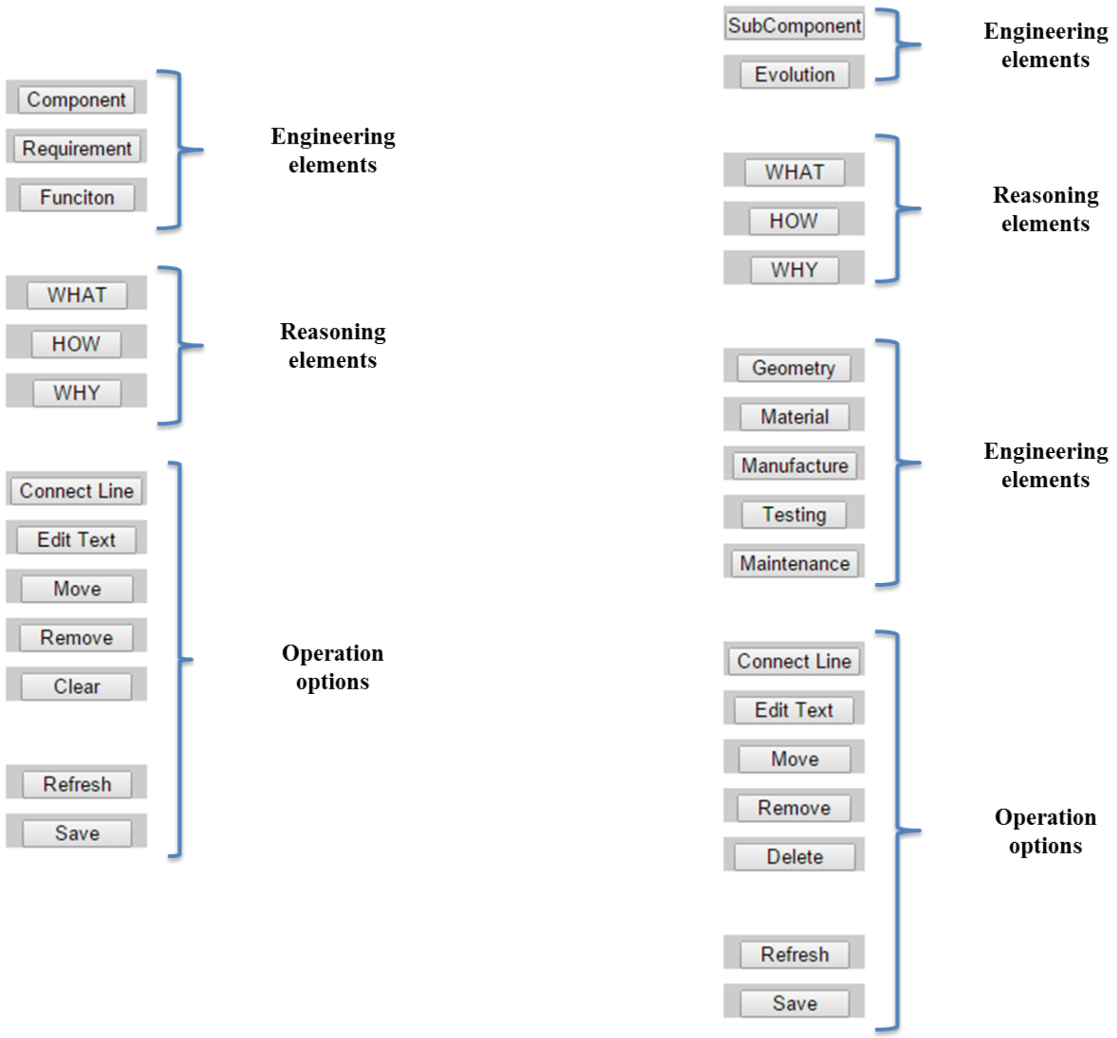


Figure 6.7. Options for the operation on canvas

The left canvas can be used for displaying multi-media information, including image, audio/video, 3D model etc. As the interface is accessed using a Web browser, it is better to use specific software to run and edit complex audio/video and 3D models, and in this case image files are more suitable for this canvas. The CAD models and engineering drawings can be attached here in the interface and saved into the database. Users can easily download it from database and open with relative CAD software packages for further operation. Also, other types of documents, e.g. text files, spread sheets, testing/simulation results can also be attached to the interface and saved into the database for further reuse. In this way, all the documents related to an artefact or component can be gathered and linked to specific design knowledge captured to explain know-what, know-how and know-why about its deliberation and development. In the following paragraphs, the main elements and functions of the knowledge capture GUI are described in details, and their relationships can be illustrated in Figure 6.8.

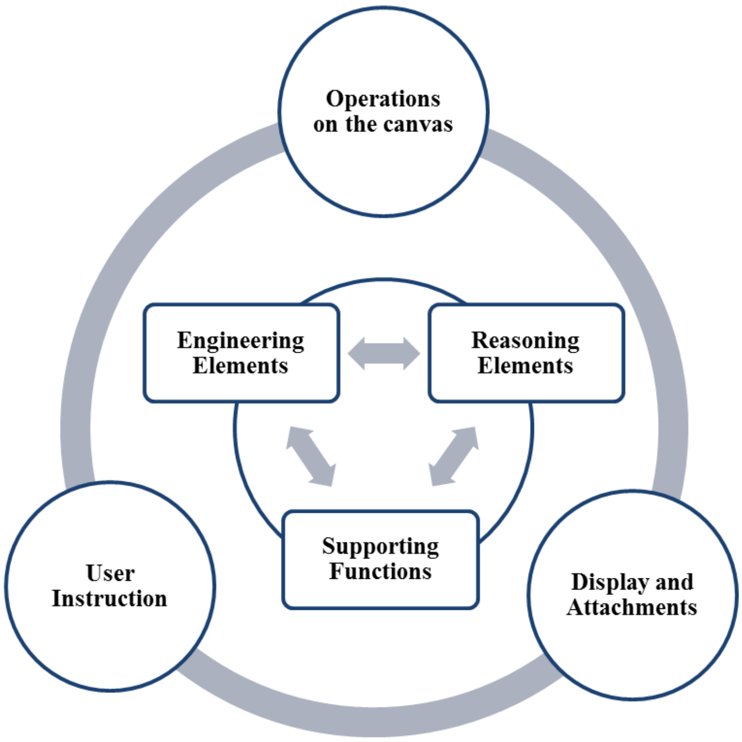


Figure 6.8. Main elements and functions of the knowledge capturing GUI

### a. The engineering element

The engineering element is the key of building a systematic framework for knowledge capturing, which includes six properties and can be divided into two categories, as shown in Figure 6.9. The six properties are four content properties (ID, Type, Position and Text) and two display properties (Shape and Colour). Specifically, 'ID' gives engineering element a unique identification, with standard format 'Name_number', e.g. Component_1; 'Type' identifies which kind of element it is, e.g. 'Component', 'Function', 'Material', etc.; 'Position' tracks both the x, y coordinates of the element on the canvas; 'Text' records the textual descriptive information of each element; 'Shape' and 'Colour' identifies the unique shape, colour and the outer frame of each element, while the centre position of the shape determines the coordinates of the element in the canvas. By setting these standard properties to these engineering elements, they can be organised and recorded clearly in the database. For more detailed classification, the engineering element includes eight main engineering elements, i.e. 'Component', 'Function', 'Evolution', 'Geometry', 'Material', 'Manufacture', 'Testing', and 'Maintenance' element, and five sub engineering elements, i.e. 'Requirement', 'sub-Component', sub-'Function', 'Expected Behaviour', 'Actual Behaviour' element. The difference between these two kinds of engineering elements lies in that when the main engineering elements are double-clicked, a window with a new canvas interface will be opened to allow further operation. In this way, the main engineering elements can be extended and more details can be added.

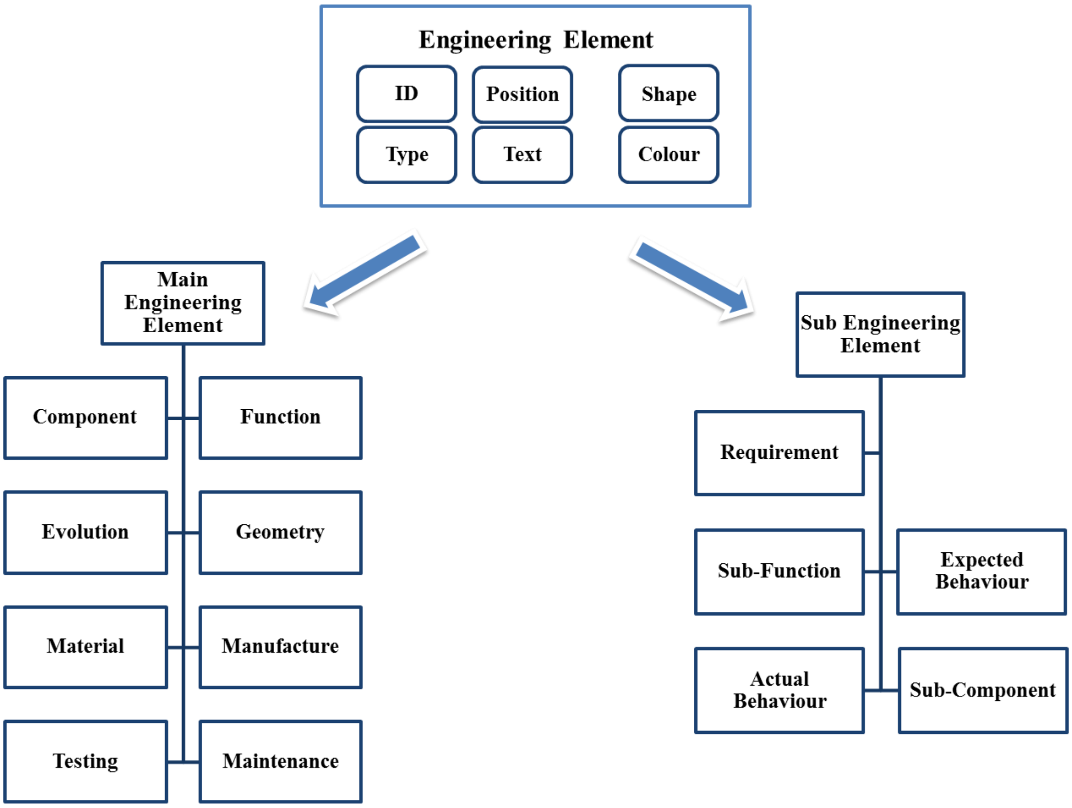


Figure 6.9. Engineering element for the knowledge capture GUI

**b. Reasoning elements**

As its name suggests, the reasoning element is used to capture various types of design knowledge exist in engineers' minds which is classified into engineering know-what, know-how and know-why, as shown in Figure 6.10. This type of element has the same properties of the engineering element. However, they only focus on recording design knowledge. The reasoning elements cannot exist separately and instead they should be created related to particular engineering elements to which they will be linked. The relationship between the reasoning elements and the engineering elements can be identified by connecting the reasoning element to relevant engineering element, e.g. linking the reasoning elements that explains why a specific structure is used for certain design to a geometry engineering element.

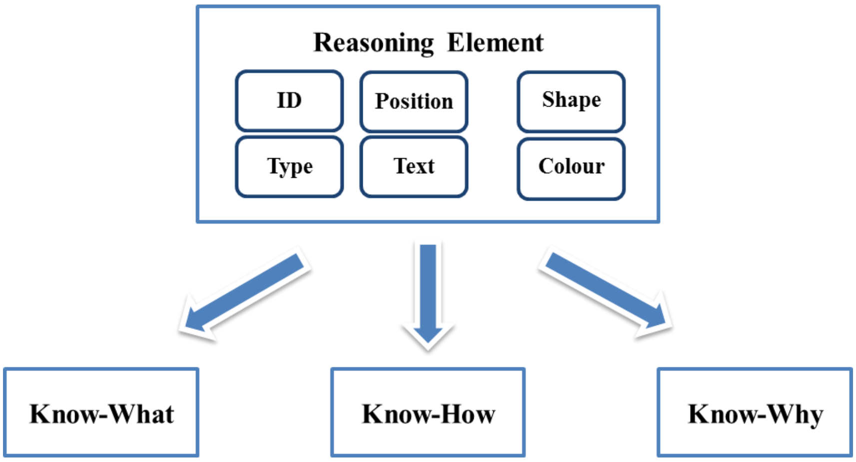


Figure 6.10. Reasoning element for the knowledge capture GUI

**c. Supporting functions**

The supporting function is used to edit the engineering and reasoning elements, as shown in Figure 6.11. There are a total of eight operating options for the system. Specifically, the Connection Line option is used to connect two different elements. In the system, a connection line can be drawn between two elements no matter what types of elements they are. However, as the connection line only has one direction, attention should be paid to which the starting element is and which the ending one is. In the system, generally, the engineering element is regarded as a starting element of a connection line and the reasoning element is regarded as the ending element rather than the other way around. The Edit Text option provides an option to modify the text added to each element within its text frame, and the Move option allows the user to change the positions of the elements on the canvas. When some elements need to be deleted, there are a few options: (1) the Remove option can delete a specific element as well as any connection lines linked to it; the Clear option will remove all the elements and lines on the canvas; and the Delete option can permanently remove all the canvas elements, lines and any attachments related to the canvas from the database. Besides, the Refresh option will refresh the page without saving any changes, and the Save option will save all the changes into the database.

**Eight Supporting Functions**

| | |
|---|---|
| **Connect Line** | • **Connect two different elements** |
| **Edit Text** | • **Modify the description of the element** |
| **Move** | • **Move the location of element** |
| **Remove** | • **Remove single element** |
| **Clear** | • **Remove all elements and lines** |
| **Delete** | • **Delete the whole canvas and relevant attachments** |
| **Refresh** | • **Refresh the canvas without saving any changes** |
| **Save** | • **Save all the changes** |

Figure 6.11. Supporting functions of the knowledge capturing GUI

### d. Attachments

There are two kinds of attachments that can be added to the canvas, namely display attachment and file attachment, as shown in Figure 6.12. Display attachment is used to display images, CAD models and multimedia information on the left canvas. For example, the user can attach an image which shows the 3D model of a component and display it on the left canvas to give engineers a visualised view on the product and component. Besides, engineering drawings, 3D models and other documents can also be attached to this knowledge capture GUI and saved into the database for further reuse. The attached documents will be assigned to specific canvases interface related to the design knowledge captured in order to provide effective retrieval and reuse.


Figure 6.12. Two kinds of attachments in the knowledge captureGUI

### e. Instructions

Under the right canvas, there is a text space for providing some operation instructions to users (No.8 in Figure 6.5). When a button is clicked or an element is created, the instruction area will show the current status and indicate the possible next steps for completing the operation task. Besides, a text hint will come out alongside the cursor when it moves to these buttons, telling the function of them.

### f. Operations on the canvas

The engineering and reasoning elements can be created by clicking on the specific button on the options bar and then click on the right canvas. The system will pop up a dialog box to allow the user to input certain descriptions to the element, and then create the specific element with the textual description on the canvas, as shown in Figure 6.13. The element will be created and placed in the location that the cursor is clicked. If the user wants to edit the description text of the element, the Edit Text option should be selected, and then a pop up dialog box will prompt the user to input new text when the element to be edited is clicked. Besides, more operations can be done on the elements, including linking two elements together, moving the location of the element, deleting the element, and saving the element into database. More details on these operations are described in the next section.

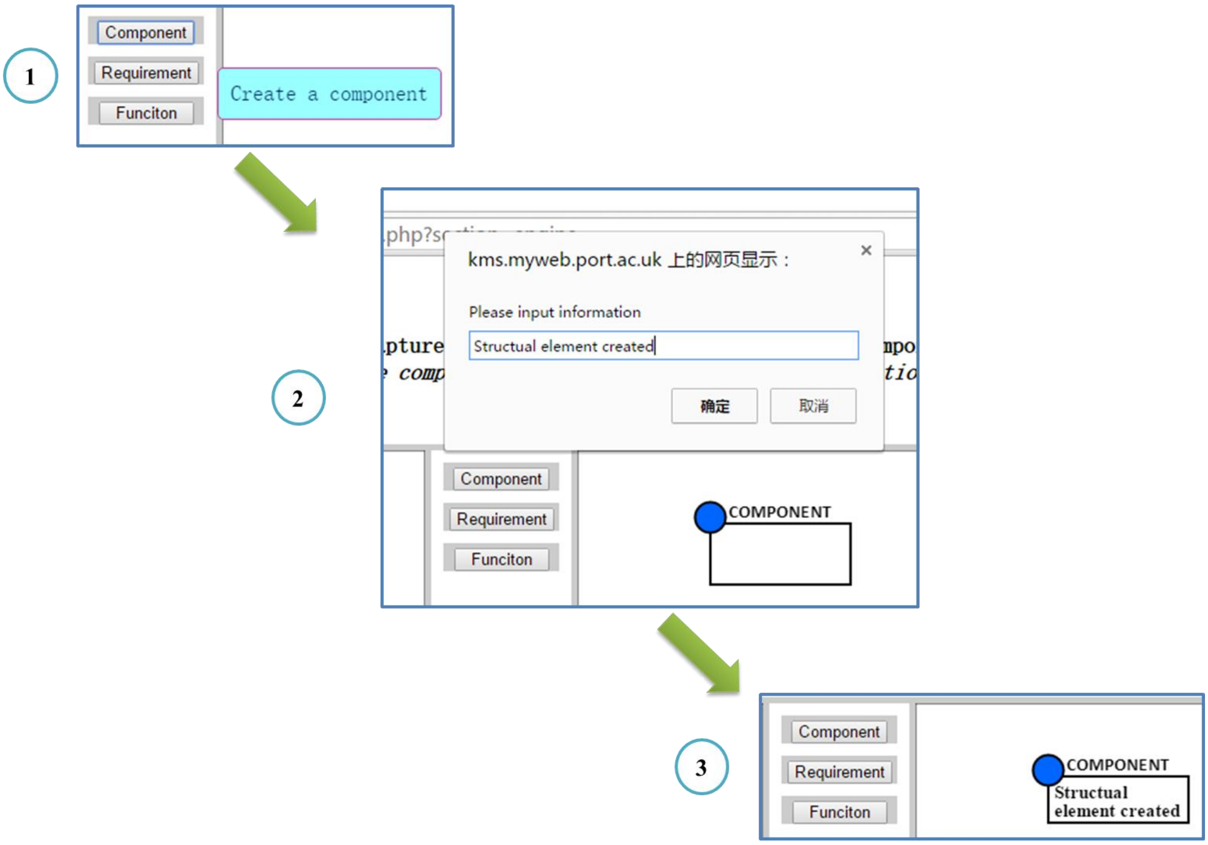


Figure 6.13. Create an element on the canvas

### 6.3.2.3 Detailed design and programming

The HTML5 and CSS3 technologies are used to build the fundamental parts of the Web-based knowledge management system whilst JavaScript is used as the main programming language for implementing the functions of the system. At the same time, PHP and MySQL are used to establish the communication between the system and the database to deal with data storage and achieve good system performance in terms of data recording and retrieval. This section describes how to achieve the key functions of the system through the programming of several important parts of the system, which will be described in the following paragraphs with their relationships shown in Figure 6.14.

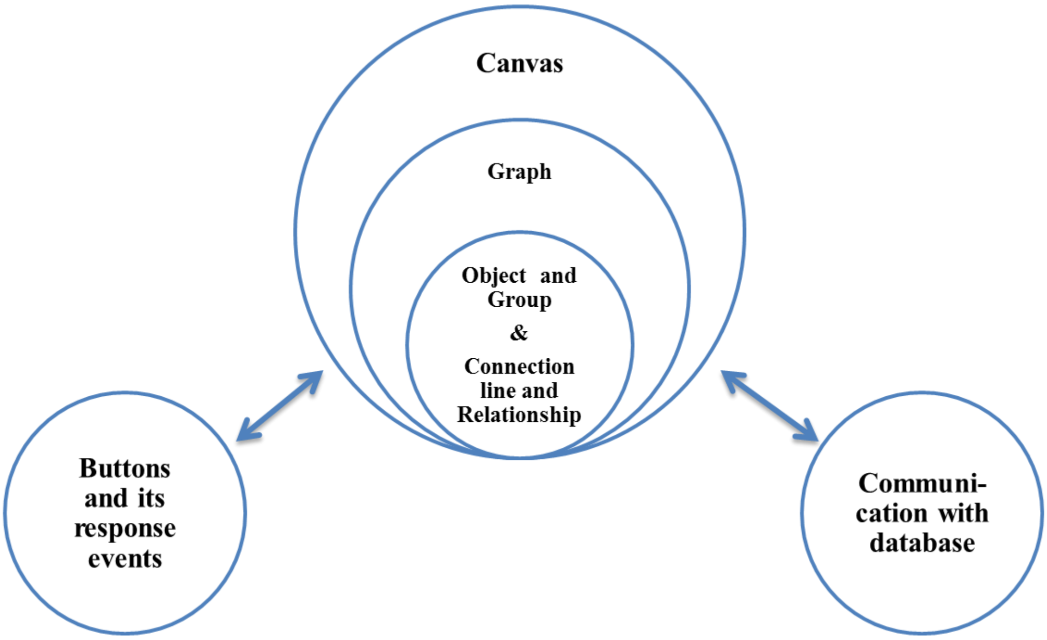


Figure 6.14. The relationship between the important parts of programming

## a. Canvas

The canvases perform an important role in the knowledge capture GUI as the system uses the proposed diagram-based RFBSE model for creating knowledge records. The canvas is implemented using the HTML5 canvas technology which provides powerful support for graphical content (2D and 3D representation) and multimedia information (audio and video contents). The actual functions within the canvases are programmed by using JavaScript. Figure 6.5 has shown that there are two canvases in the knowledge capture GUI, left canvas and right canvas. As the left canvas is used for displaying images and CAD models, a file reader created by JavaScript is needed to read files from the local computer system and subsequently transfer them to the webpage and display them in the canvas. The right canvas is the main part of the knowledge capture GUI, and thus it is more complicated and its details are described in the following paragraphs.

### b. Graph

In order to create engineering and reasoning elements on the right canvas, a blank layer should be firstly added as drawing background. At the same time, a click event is added to the background. When the canvas background is clicked, the location of the cursor will be remembered and further events will be triggered after clicking. In order to clearly manage the graphical information in the database, all the elements and lines created in the right canvas within the same webpage are regarded as a graph and thus saved in the graph table in the database. In this way, different kinds of information within the same webpage can be easily searched as they are in the same graph.

### c. Object and group

Both engineering and reasoning elements can be created on the canvas with a certain set of properties, and they are regarded as element objects. When it is created using JavaScript object constructor function, the ID, type, and current location of the element object will be determined. Specifically, the ID of the engineering or reasoning element is generated by a separate JavaScript function which returns a string as a unique ID indicating the type of the element and the unique number, e.g. ‘Component_001’; the type of the element object is depended on which button in the option bar is clicked, such as ‘Requirement’, ‘Function’; the location is obtained from the position of the cursor on the canvas when the left button of the mouse is clicked, including the x and y coordinates of the cursor on the canvas. With these properties, an element object can be created. In order to identify different kinds of element object, a shape such as circle or rectangle is given to the element object with various colours. Apart from that, an adjustable textbox is attached to each element object for describing the content of the engineering or reasoning element. All of these properties are combined together as a group so as to make it more efficient to conduct operations on the whole element object. Besides, several JavaScript events are added to the element object for specific operations. These events are basically concerned with various cursor operations, such as pressing, releasing, clicking, double-clicking, dragging, etc., and they are used and explained in the next two sections.

**d. Connection line and relationship**

Detecting the relationships between different element objects is an important task for the programming, and it is mainly achieved by creating connection lines between element objects. Connection line is created by a JavaScript line object constructor which contains the ID of the line object as well as the IDs of the two element objects the line is connecting. The ID of the line object is also created through a separate JavaScript function to obtain a string consisting of the word ‘Line’ and a unique number, e.g. ‘Line_001’. The ID of the element objects can be obtained by their own built-in events which can be triggered by the line object constructor. The process of creating a connection arrow line is shown in Figure 6.15 with three steps. Firstly, the connection line button should be clicked, and all the elements on the canvas will be set as still. Then, move the cursor to the first element to be connected and press the left button of the mouse.

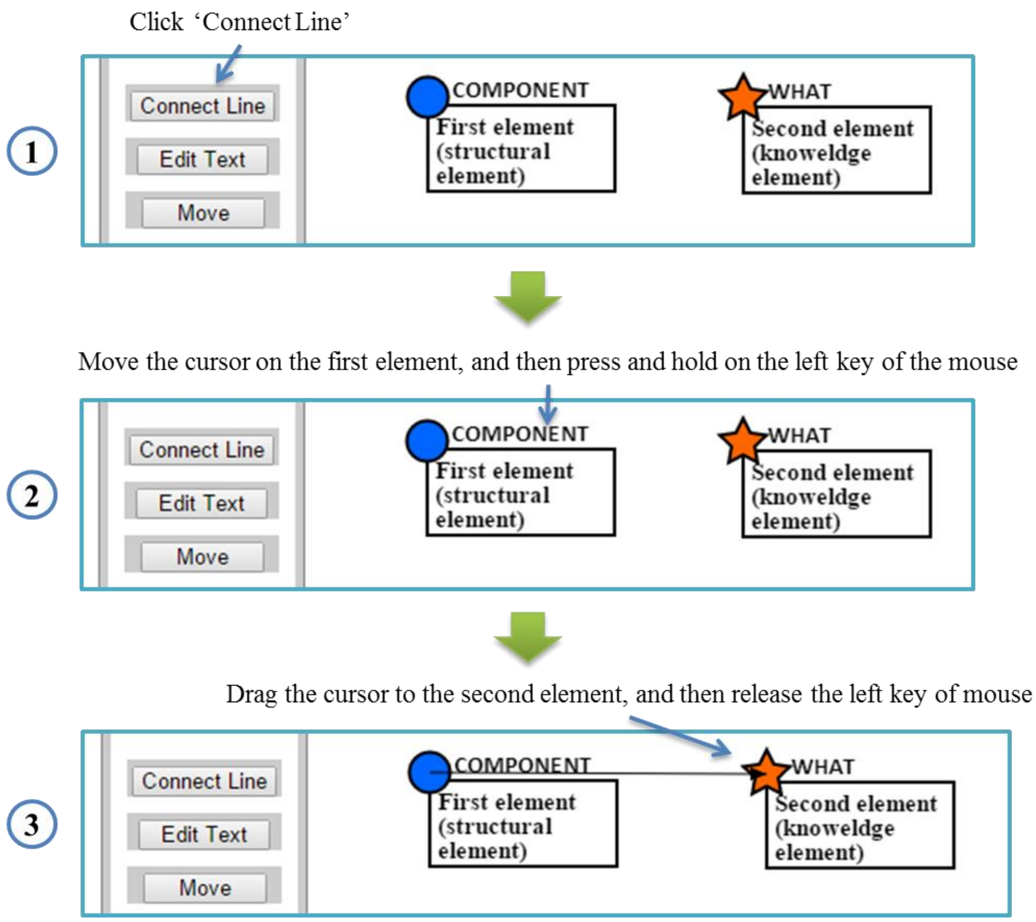


Figure 6.15. Draw a connection line between two elements

At this point, the 'mouse down' built-in event responses and records the ID of this element, and a hint will be shown under the canvas reminding the next step: "Please drag the cursor to the element you want to connect and then release". Following this instruction, the cursor should be dragged to the second element object while the left button of the mouse should be kept pressing during this dragging process. As soon as the left button of the mouse released, another built-in event 'mouse up' in the element object will be triggered and its ID will be recorded. With the IDs of the first and second element object, the locations (x and y coordinates) of them can be detected by the line object constructor function and a connection arrow line will be created linking from the first element object to the section one. At the same time, the ID information of these two element objects and the created line object will be added into several JavaScript global arrays, e.g. data-saving array and temporary-data array, for further operations. They record the relationships between different elements, which are useful for their retrieval and reuse.

**e. Buttons and its response events**

Apart from the creation of the element and line objects, several JavaScript events are activated by the buttons in the option bar (the category of the buttons has been shown in Figure 6.7). The buttons for creating engineering and reasoning element are similar, which mainly set the type of element and activate the element creating function. The operation function buttons have specific usages, as shown in Table 6.1.

Table 6.1. The programming events behind the operation buttons

| Button | Usage |
|---|---|
| Connect line Button | Set all the elements on the canvas still and change the logic key for connecting line to be 'true' |
| Move Button | Reset all the elements on canvas to make them movable |
| Text Button | Active Edit Text function to allow users to edit the textual content of an element object by triggering the built-in event inside it |
| Remove Button | Trigger the 'Remove' built-in event within an element object to delete the element object when it is clicked. |
| Clear Button | Active the 'Clear' function to remove all the elements and lines on the canvas |
| Delete Button | Delete all the elements, lines and attachments related to the canvas interface from the database |
| Refresh Button | Reload the webpage without saving any changes |
| Save Button | Activate the JavaScript saving function to save all the changes into the database, and refresh webpage simultaneously |

The programming behind the buttons focuses on defending the type of the button, e.g. type = 'Requirement', set the Boolean value of logic keys, e.g. 'isDrawGroup = true', and activate specific JavaScript function. Thus, once a button is clicked, the values set behind the button can be sent to the system, and specific event will be activated to perform relevant function.

### f. Communication with the database

There are several JavaScript global arrays created in the system, which are used to store the data within the array memory so that they can be used by programming. These arrays can be divided into three types, data-saving array, temperate-data array, and change array. The specific functions of these three arrays are describe in Table 6.2

Table 6.2. Three types of JavaScript arrays used in the system

| Types | Function |
|---|---|
| Data-saving Array | Record the newly created data from canvas |
| | Store the existing data loaded from the database |
| Temperate-data Array | Record the newly created data |
| | Use in the JavaScript saving function to save data into the database |
| Change Array | Used as a intermedia that record the changes made during several operations |
| | Adjust the temperate-data array before the saving functions activated |

With these three types of array, the data can be managed clearly before and during the system's communication with the database. There are several saving functions created through JavaScript and PHP programing, including save element, save connection line, save the relationship between element and connection line, save image, update the position of the element, and update the text of the element. Apart from these saving functions, there are also functions for loading data from the database, e.g. loading graph, loading object, loading line, etc., and removing elements , lines, and their relationships from the database. All of these functions are used for the communication with the database, as shown in Figure 6.16. Also, AJAX technology is used for the effective communication, and PHP files are also used as intermedia for the communication and operation with the database. More details on the database will be described and explained in the database application section.

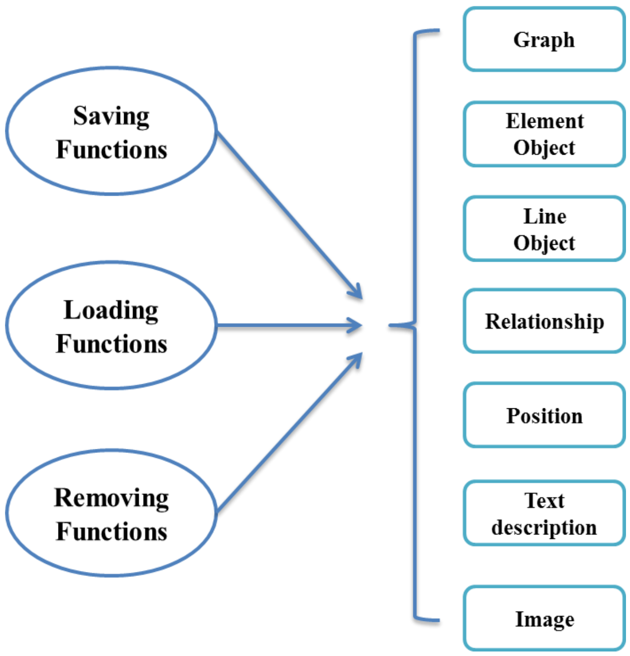


Figure 6.16. Three types of functions used for the communication between the system and the database

## 6.3.3 Database design and development

### 6.3.3.1 Database design

The database design is focused on how to organise and store the design information and knowledge captured in the system for future reuse. As described in Section 6.3.2, the engineering elements, reasoning elements and their connection lines are the main parts in the knowledge capture GUI, and thus relative tables should be created in the database to store the data they contained, as shown in Figure 6.17.

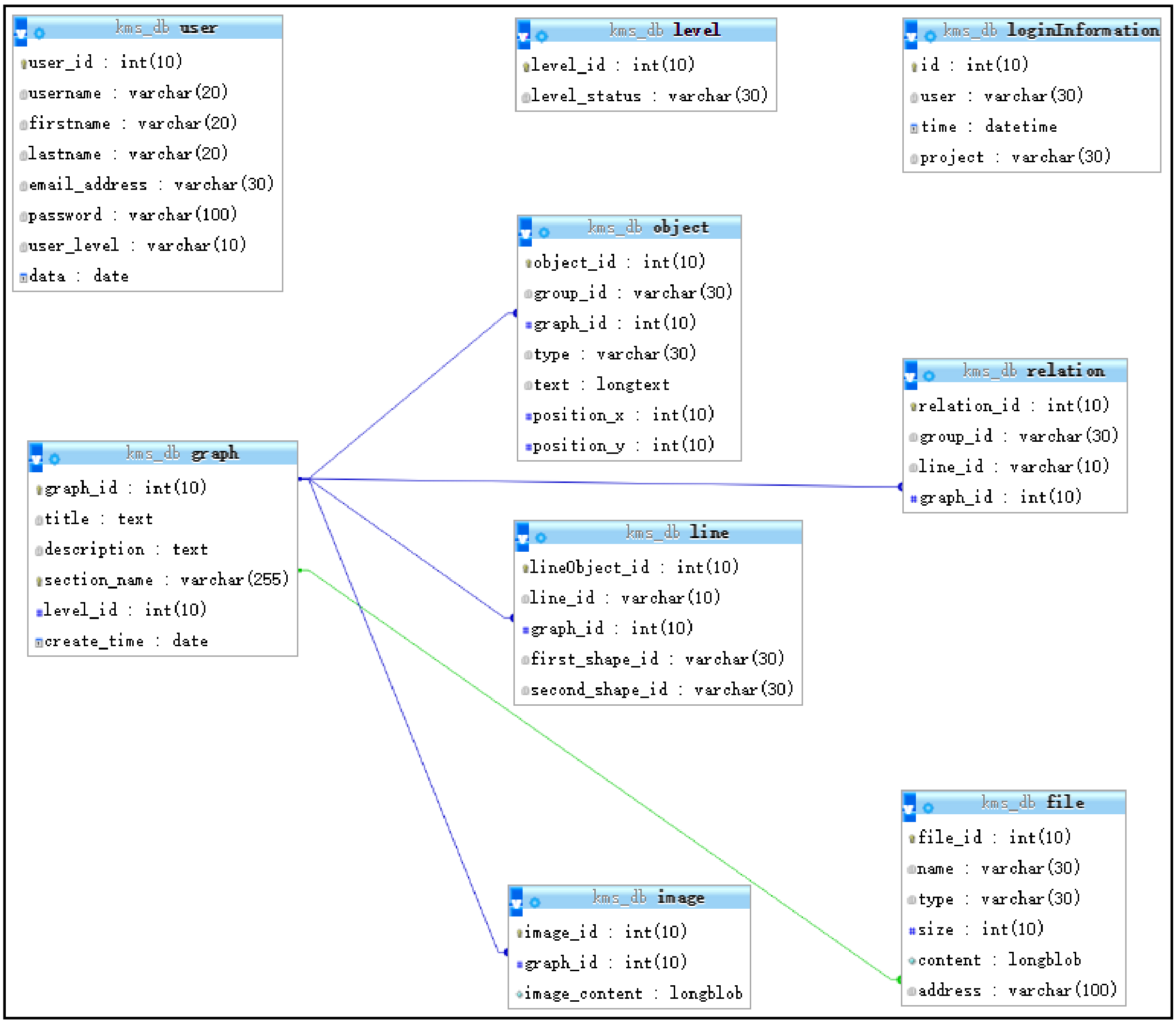


Figure 6.17. Database tables design

In order to improve the effectiveness of data management, a graph table is firstly created to manage the location of all the elements, lines and attachments in the database. A object table and line table are creates respectively for storing the data on element objects and connection line objects. Also, a relationship table is required and created to record the relation between each element object and specific lines connected to it. There are two tables created for the attachments: one is for the image/CAD models for displaying purpose; another one is for the files uploaded to the database or the address of the files in local computer storage or on a Web space. Apart from these, there are three tables for storing information about the users, namely user, user level and login/logout information respectively. Therefore, the tables in the database have been designed in three main types, i.e. canvas inputs and attachments, system information.

**a. Tables for canvas inputs**

The graph table can be regarded as the centre for linking the other tables together, as all the elements, lines created on the canvas and the attachments uploaded are added an indicator showing which graph table they are belong to. Thus, the function of the graph table is to locate the position of the relevant data in the database, with four characteristics, i.e. title, description, section name and created time. The tables for the element object and the line object are similar, both of which are used for recording the properties of the objects as well as a link to the specific graph they are belong to. It should be noticed that the coordinates of the object on the canvas are stored in a separate column, i.e. recording x and y coordinate separately. This allows the ordinates to be loaded as a single number instead of an array, which makes the programming more efficient. For the relationship table, it is mainly used for recording the connection lines linked to each element as well as the element itself in order to track the relations between elements object and its connection lines. Through the determined relationship, the connection line objects can be modified at the same time when the element objects are moved or deleted, which can make the modification more efficient.

**b. Tables for attachments**

There are two types of attachments in the system: one is for displaying information and another is for data storage, thus two tables are created separately for storing these two kinds of attachments respectively. Specifically, the image table stores the images or

CAD models to be shown on the left canvas in the knowledge capture GUI. To achieve good quality of displaying information, the images or CAD models are adjusted by the JavaScript functions on the Web browser and in this sense the images shown on the canvas are not the original documents but the ones that more suitable for the Web environment. Different from this display information, the data saved in the file table in the database are original documents which can be downloaded from the database and opened using relative software packages. For some files with extra-large size, only their addresses of storage locations will be recorded in the table, and the user can find them through tracking these addresses.

**c. Tables for system information**

The system information tables record the user information, user level, and user login information. Specifically, the user information table saves the information on each user's account, including username, first name, last name, email address, password, user level, date of creation, etc. The user level table can record the details on the roles of different users and specify their levels of authorities for accessing and editing the contents in the system. The login information table records the time at which a user accesses the system and the project he/she is undertaking. The information stored in these tables can also be used to analyse the working statuses and context for users' individual working spaces so that better in-context recommendations can be made to the users.

### 6.3.3.2 Database development and application

The tables of the database are created based on the idea explained in the above section and by using the SQL language. Apart from the tables, several PHP files are created to create related functions for communicating with the database. Firstly, a common PHP file with the server name, user name, user password and database name should be created to connect to the database. The other PHP files created make references to this database connect file and undertake further operations such as saving, loading and editing data. The relationships between the system, PHP files and the database can be illustrated in Figure 6.18.

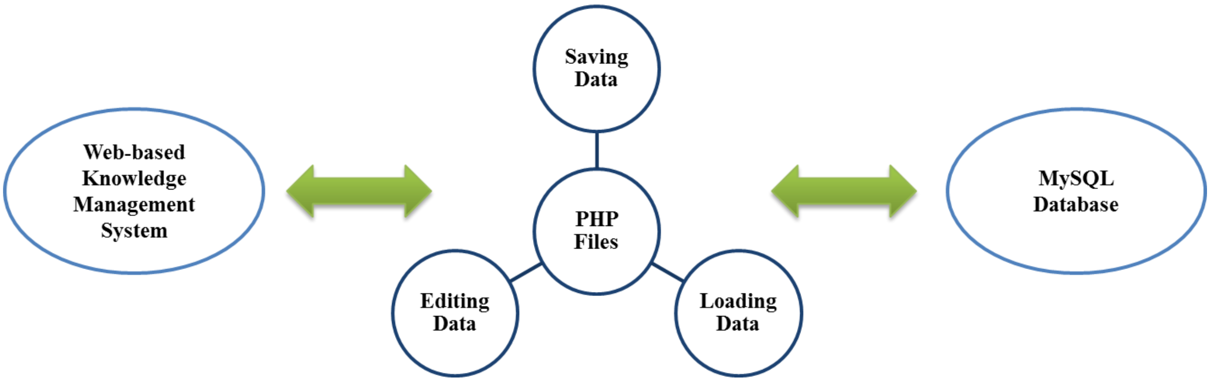


Figure 6.18. The relations between the system, PHP files and the database

#### a. Saving data

The PHP files for saving data are used to save the data into graph, element object, line object, relationship, image, and attachment tables. The common part of them is to use the 'Insert' SQL function to save the relevant data into specific tables in the database, and this function is written within the PHP files, which can be activated through the JavaScript function in the system. In the JavaScript programming of the system, the data to be saved to the database are stored in the temperate-data array (mentioned in the Section 6.3.2.3). When the 'Save' button in the option bar of the system is clicked, the

JavaScript saving function in the system will be activated and the data in the temperate-data array are transferred to relative PHP files in order to 'Insert' them into the database.

**b. Loading data**

Different from saving data files, the loading data files focus on the output of data from database for further use. The idea is to load multi-data in the same row of a table and link them with some symbols, e.g. '+' and '^', for building a long string. For example, the data loaded from the element object table has the output:

"$row['group_id'].'^'.$row['type'].'^.$row['position_x'].'^'. $row[position_y'].'^'.
$row['text'].'^'. $row['object_id'].'+';".

It is a long string with group ID, type, coordinates, description text and object ID. This string will be parsed and used by JavaScript functions in the system, and the symbols '+' and '^' are used to make the parsing process more efficient.

The PHP files for loading data are created to be used in various JavaScript functions. When a user open an exist engineering design project in the system, a JavaScript loading data event will be activated, and then the relative PHP loading data files are used to communicate with the database and retrieve relevant data to be displayed in the system interface. Also, the loading PHP files may be used during the user operations on the knowledge capture GUI. For instance, when the user drags an element object to a new location, a JavaScript function will use a PHP loading data file to search in the database on the lines connected to the element object and obtain their information in order to move the lines together with the element object.

**c. Editing data**

There are several types of PHP files for editing data, including creating, removing, and updating data. The creating function is mainly used to create a new graph. When an engineering element on the canvas is double-clicked, a new graph is created and adds to the graph table in the database through the support of a PHP editing data file. The removing data files are used to remove a single object or a whole graph with all the elements and lines as well as the uploaded documents related to the graph. The updating data files are used with the JavaScript updating functions in the system to update the current positon of an element object or its textual description.

Apart from the PHP files mentioned above, there are also some other files for specific system applications, including login/logout, registration and searching for information. All of these PHP files aim to ensure the communication between the system and database effectively and efficiently.

## 6.4 Discussion

In this chapter, the methodology of capturing integrated design knowledge through the design process has been proposed. Based on this methodology, a concept of the next-generation knowledge management system has been proposed. The main idea of this system is to capture integrated knowledge space that can be further linked to useful data and information for their effective reuse, in the wake of the missing capacity of capturing tacit knowledge and experience as well as useful design context in the existing knowledge management systems. This is the concept of a knowledge-centred solution which is different from the traditional data-centred systems. The design and development of a prototype system is detailed in this chapter to explain what functions are needed to implement the methodology as well as the key enabling technologies that can be used to develop advanced knowledge management solutions.

Within the environment of globalisation and collaborative working, a knowledge management system should be able to support knowledge capture and reuse in the Internet-distributed environment. In this case, multi users from distributed locations can use the Web-based system to discuss and edit the same piece of design knowledge both synchronously and asynchronously. Moreover, engineers from different stages of a project can contribute to the specific section by recording their design information and knowledge, and they can also access the required information and knowledge from other stages to support their current work. For example, design engineers can access manufacture information and knowledge in order to produce a better design. Also, this system can support collaborative working during communication between design engineers by helping them record the useful knowledge generated during this process in a timely manner.

The focus of the system is in capturing, representing and reusing design knowledge and at the same time finding and organising useful data and information related to the knowledge. Different from the traditional knowledge management systems which are mainly focused on product data, this system concentrates on the design knowledge and regards the relevant data and information as attachments. Specifically, the system requires the user to build a systematic framework in order to provide a clear context to capture the design knowledge of an artefact or a component, and then organises the relevant data and information as attachments that allows them to be reused together with the specific design knowledge. As the engineers use the RFBSE model as guidance to capture design knowledge alongside the design process, the system enables knowledge capture as an integral part of a design project instead of being done retrospectively.

## 6.5 Summary

A Web-based knowledge management system for engineering design has been designed and developed in this research to capture design knowledge for effective reuse. The system is based on a knowledge-centred concept, which focuses on capturing, organising and representing tacit design knowledge integrated with formal design objects and processes. Additionally, the system uses a model-based representation, emphasising the importance of using the RFBSE model to guide the engineers in capturing and organising design information and knowledge. In order to support a collaborative working environment, the system uses P3 model to build the framework and has been developed as a Web-based system using several newly developed Web technologies. Also, these technologies can enable the representation of graphical and multimedia information on webpages, providing a much more powerful way of presenting design knowledge and supporting a collaborative working environment through the system. With the concept of knowledge-centred solutions and the application of the-state-of-the-art information technologies, the design and development of this prototype Web-based knowledge management system helps move towards the next-generation of knowledge management systems by providing useful models, methodologies and enabling technologies.

# Chapter 7

# Application and Evaluation

## 7.1 Introduction

The purpose of this research is to explore a systematic method to capture useful design knowledge and experience for future reuse. To better explain and apply this method, Chapter 5 has explained the fundamental part of the RFBSE knowledge representation model and how to use it in capturing useful design knowledge and experience theoretically, while Chapter 6 has detailed the systematic method through the design and development of a Web-based knowledge management system for capturing various pieces of knowledge and arranging them into an integrated representation. This chapter aims to evaluate the proposed RFBSE model and the developed prototypal system by applying them to solve real engineering design problems. This evaluation can be divided into two levels, namely a theoretical level and a system level. Specifically, the theoretical level application mainly focuses on using the RFBSE model to capture and represent design knowledge through a complete engineering design project. Through this application example, the procedure of using the model to support undertaking the knowledge management tasks through design process is identified. The system level application is to apply the Web-based knowledge management system in various engineering projects to evaluate the system's capabilities in undertaking knowledge capture and reuse in different aspects. Three projects have been chosen for the system application: the first one is a complete engineering design project which is also used in the theoretical level application; the second one is focused on capturing design knowledge from a process of design evolution; and the third one is on capturing information and knowledge from a service and maintenance project. These three projects are deliberately chosen to demonstrate the functionality of the Web-based knowledge system in various areas. Details of these two levels of applications are described in the following sections, together with the evaluation on the model and methods involved.

## 7.2 Theoretical application

### 7.2.1 Overview

The RFBSE model is a knowledge representation model, aiming to guide engineers to capture useful design knowledge and experience during the engineering design process. It not only identifies the key reasoning elements and their relationships within an engineering design, but also provides a method on the capture and representation of integrated design knowledge. Specifically, the RFBSE model is firstly used to identify the requirements, functions, behaviours and structures of a design artefact or component, and on this basis discover the design knowledge used to solve problems in four design activities, namely functional decomposition, expected behaviour analysis, structural decomposition and actual behaviour evaluation. Also, the knowledge generated through design evolution will be highlighted and captured. Then, the knowledge discovered is represented through as a range of diagrams explaining what issues were considered, how to solve problems as well as why to take specific considerations and decisions. The detailed procedure is explained using an engineering design project in Section 7.2.2. Also, an evaluation of the RFBSE model is undertaken by comparing it to several previous proposed models in Section 7.2.3.

### 7.2.2 Using the RFBSE model to capture design knowledge

The basic idea of the RFBSE model has been explained in Section 5.3.3 and this section aims to give more details based on an engineering design project, i.e. an intake system design from the Formula Student racing car design project. An intake system is an important part of a vehicle' powertrain, which controls the amount of air flown into the engine and subsequently adjusts the fuel supply based on the air flow rate. The RFBSE model is used as a guidance to capture designers' useful knowledge and experience through the design process of this system. At the beginning of the process, customer requirements are gathered and analysed, and then the functions which can be used to meet these requirements are explored. These functions are the objectives to be achieved and can be further decomposed into several sub-functions in order to clarify and simplify the tasks, as shown in Figure 7.1.

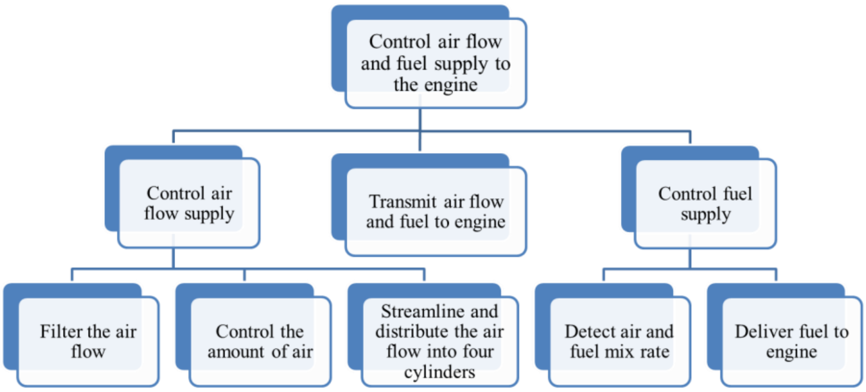


Figure 7.1. Functional decomposition of the intake system

During this process, design knowledge predominantly exists in two aspects—one is what functions are needed to meet certain requirements and another is on what sort of sub-functions are needed to realise the overall function, how they will work together and why a particular sub-function is used. These kinds of knowledge can generally be captured in the form of know-what, know-how, and know-why, as shown in Figure 7.2

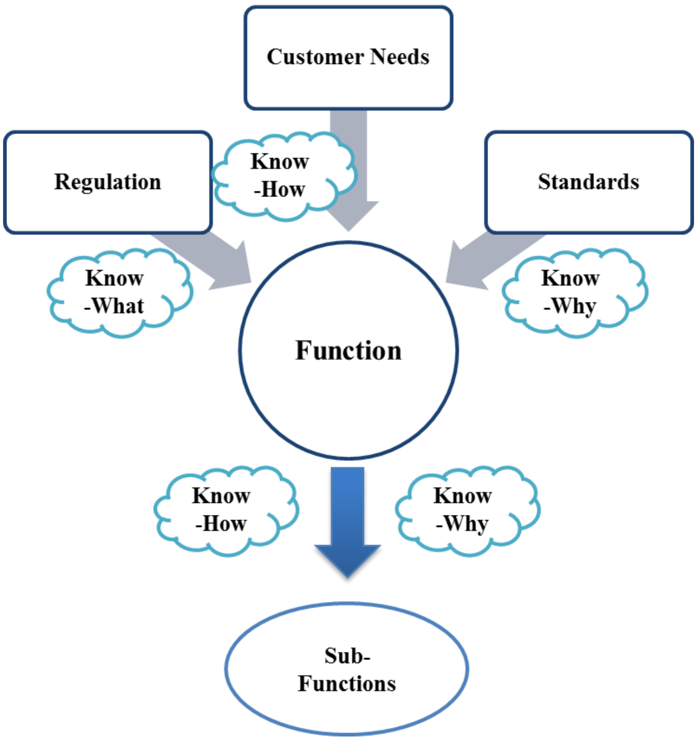


Figure 7.2. Capturing design knowledge through requirement analysis and functional decomposition

The above functions and sub-functions will be transformed to expected behaviours which are the ideal results for achieving the certain functions. During these transformations, a range of idea generation and evaluation are undertaken by the designers, which is the expected behaviour analysis task mentioned in the RFBSE model. Through this task, solutions need to be generated and important decisions need to be made, particularly in the transformation from functional descriptions into performance requirements and then into the specific status and parameters, as shown in Figure 7.3. The underlying knowledge holds the key in deciding what are the right issues need to be solved, how to solve these issues and why to take the particular actions and decisions. Thus, it should be captured in the form of know-what, know-how and know-why.

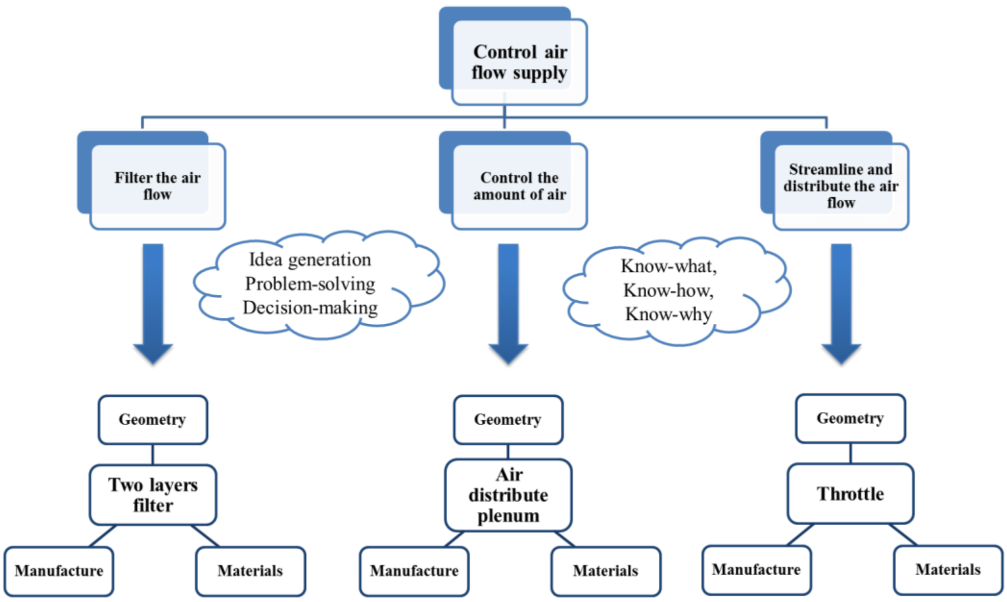


Figure 7.3. Capturing design knowledge through expected behaviour analysis

In order to give forms to the components of an artefact effectively, structural decomposition is undertaken to establish an optimal layout for the artefact and identify the special and physical relationships between different components. In this intake design example, the intake system has been decomposed into five components, namely air filter, throttle, intake plenum, connector, and fuel injector, as shown in Figure 7.4. Generally, a structural decomposition results in a number of components, each of which performs a particular function. Take the air intake system as an example, each component in Figure 7.4 realises a specific function that the system needs to perform. Specifically, the air filter is used to filter the air flowing into the engine; the throttle controls the amount of air; the intake plenum streamlines the air flow and distributes it into four parts which connect to the four cylinders of the engine; the connecter determines the location of the intake system and connect it to the engine; and the fuel injector controls the amount of fuel supply to the engine.

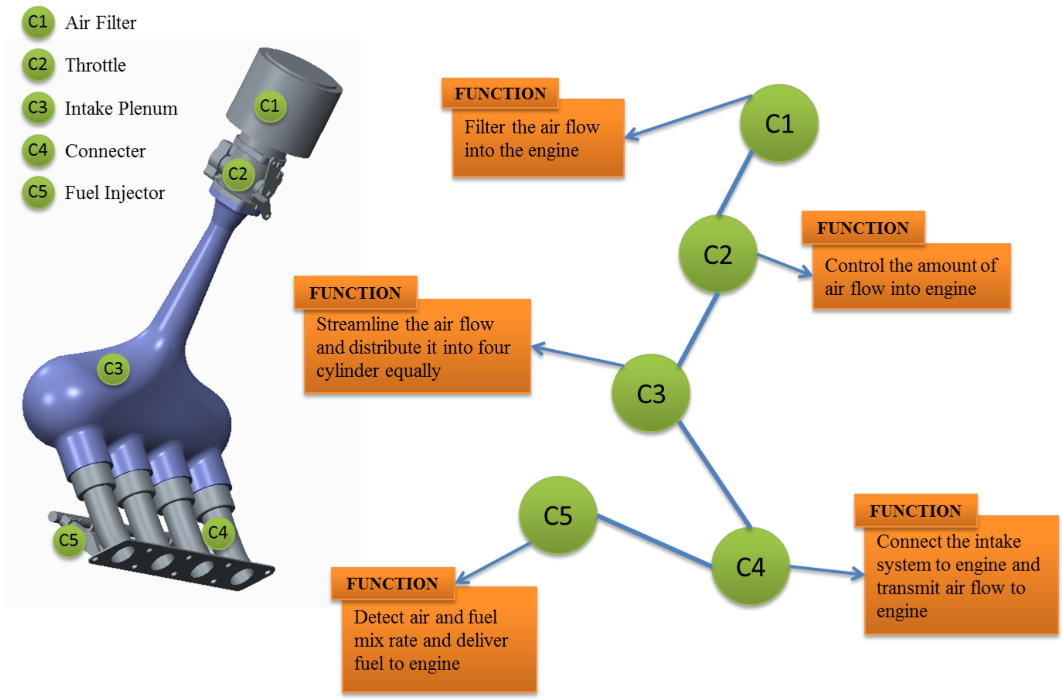


Figure 7.4. Structural decomposition of the intake system

For each component, it can be further divided into several sub-components if functions performed by these sub-components need to be analysed separately to facilitate problem solving and understanding. With this structural decomposition, useful design information and knowledge related to the intake system can be organised in a systematic way. Such a structural decomposition not only provides a straightforward way of understanding the relationships between different components but also combines the geometric information of component with rich design contexts for better reusing the underlying design knowledge, as shown in Figure 7.5.

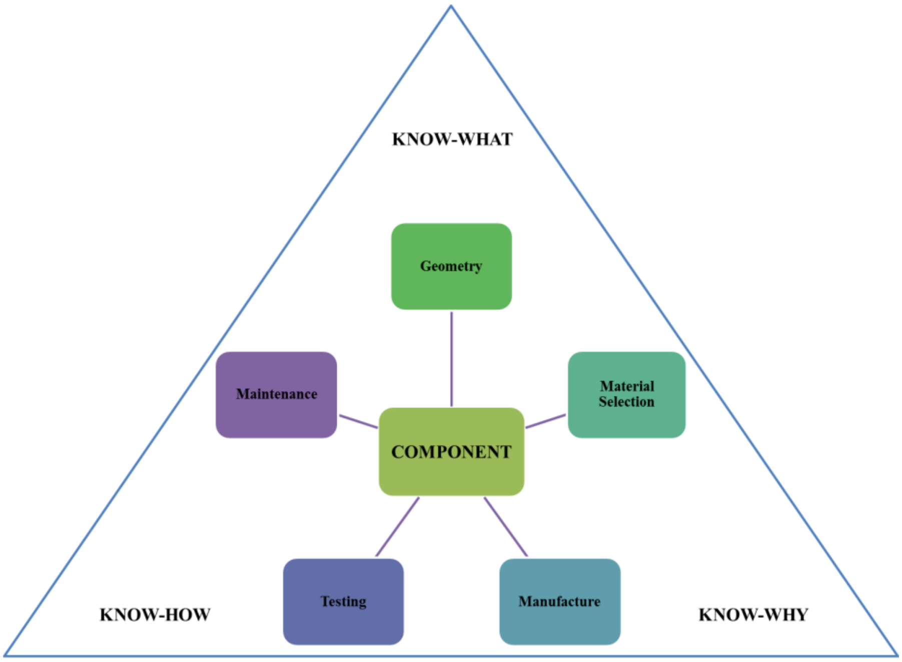


Figure 7.5. Capturing design knowledge within a specific context

Moreover, useful design knowledge will also be generated through the changes and improvements made on the existing designs. With the embodiments of these components, their actual behaviours are determined and can be evaluated by comparing with their expected behaviours identified previously. Figure 7.6 gives an example of the intake plenum to explain the actual behaviour evaluation process through which necessary changes and improvements are continuously made in order to make the actual behaviour close to the expected behaviour as much as possible. This process involves a large amount of knowledge related to what issues to consider, how to improve performances and why to make a particular change, etc. Therefore, the evolution component of the RFBSE model can be used in this task to capture the decision-making process in achieving an optimal solution.

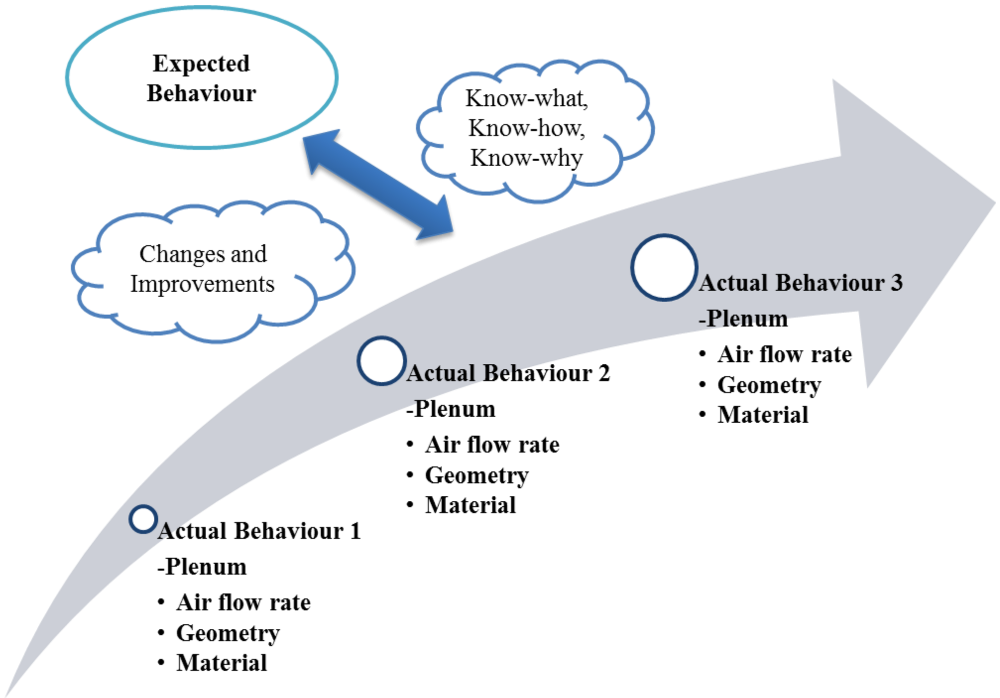


Figure 7.6. Capture design knowledge through actual behaviour evaluation

Overall, with the guidance of the RFBSE model, useful design knowledge generated during the design process can be identified and captured. Also, the model supports the problem solving process by providing a number of specific design tasks through which useful knowledge is generated together with a complete and clear design context for its effective reuse.

### 7.2.3 Evaluation of the model

Apart from demonstrating the application of the RFBSE model in a practical engineering design project, the model has also been compared with previous models for evaluation. From early research in the area of describing design objects and design processes for engineering design, several models have been proposed including the Function-Behaviour-Structure (FBS) model (Gero, 1990), the Functional Representation(FR) model (Sembugamoorthy & Chandrasekaran, 1986), the Structure-Behaviour-Function(SBF) model (Bhatta & Goel, 1994), the prescriptive model of engineering design process (Pahl et al., 2007), and Design Rationale (Bracewell et al., 2009). Compared to these models, the RFBSE model has a distinct feature of enabling an integrated knowledge representation, which employs the concepts of function, behaviour and structure in Gero's FBS model for describing design objects whilst incorporating another two important elements, namely requirement and evolution. Function, Behaviour and Structure are the three classic elements widely accepted by researchers for describing design objects. Since the RFBSE model is proposed to capture and represent design knowledge, it not only uses these elements to describe knowledge about design objects but also focuses on the links between these elements and the problem solving and decision-making processes in the tasks of functional analysis, structural decomposition, and behaviour analysis and evaluation. In addition, the requirement element is employed in the model as it determines the goals of the design project. Moreover, the transformation of a requirement into specific functions involves highly useful knowledge related to understanding customer needs and establishing an effective functional structure particularly in the context of customer-centred design and customisation. The last element of the RFBSE model is design evolution which considers the dynamics characteristic of design knowledge and focuses on capturing the design knowledge generated on design changes and improvements as well as designers' evolving knowledge needs.

A number of factors have been proposed to be used as the criteria for evaluating the knowledge models, which involve three main areas: model description, application in knowledge representation and implementation by computer support tools. On this basis, a number of comparisons have been made between the RFBSE model and existing knowledge models. Specifically, the models chosen for comparison include: (1) FBS (Gero, 1990) and its variants such as RFBS (Christophe, Bernard, & Coatanea, 2010) and FCBS (Gu, Hu, Peng, & Li, 2012); (2) FR (Sembugamoorthy & Chandrasekaran, 1986) and its extension CFRL (Iwasaki et al., 1993); (3) SBF (Bhatta & Goel, 1994); (4) Design Rationale model (Bracewell et al., 2009); and (5) Pahl' design process model (2007). The details of the comparison are summarised in Table 7.1.

Table 7.1. Comparison of the RFBSE model with several similar previous models

| | | FBS | RFBS | FCBS | FR/CFRL | SBF | Design Rationale | Pahl's Design Process Model | RFBSE |
|---|---|---|---|---|---|---|---|---|---|
| **Model Description** | **Subject of Description** | Design objects and their relationships | Extend FBS and implement in SysML | Extend FBS with functional cell | Functional modelling | Analogical reasoning | Design rationale | Design process | Knowledge representation and reuse |
| | **Systematic Description of design objects or design process** | Function, Behaviour, Structure | Requirement, Function, Behaviour, Structure | Function, Functional cell, Behaviour, Structure | Functional decomposition | Structure, Behaviour, Function | Problem solving process | Engineering design process | Requirement, Function, Behaviour, Structure, Evolution |
| | **Capture design changes and evolution** | No | No | No | No | No | Yes | No | Yes |
| | **Capture design knowledge context** | No | No | Yes | No | No | Yes | No | Yes |
| **Application on knowledge capture and reuse** | **Knowledge representation** | Abstract schema | SysML diagram | Functional cells | Functional decomposition | Analogy reasoning | Graphic representation | Procedure representation | Graphic representation |
| | **Integration of multi-faceted knowledge** | N/A | N/A | N/A | N/A | N/A | N/A | N/A | Yes |
| | **Confidence of reuse** | Medium | Medium | High | Medium | High | High | Medium | High |
| | **Support for design knowledge reuse** | Conceptual design process | Conceptual design process | Conceptual design process | Conceptual design process | Analogical design and case-based reasoning | Capture design rationale through design process | Describing design process | Capture design knowledge during design process |
| **Implementation by computer tool** | **Applicable computer-aided tool** | N/A | Using SysML for modelling | Computer-aided conceptual design tool | N/A | IDEAL | DRed | N/A | Web-based knowledge management system |
| | **Representation in software** | N/A | SysML diagram | Functional sketches | N/A | Case-based reasoning | Design rationale diagram | N/A | Graphic knowledge representation diagram |
| | **Support for collaborative working environment** | N/A | No | No | N/A | No | Yes | N/A | Yes |
| | **Extendibility** | N/A | Medium | Medium | N/A | Low | High | N/A | High |

#### 7.2.3.1 Model description

In terms of the model description aspect, the object and focus of each model is analysed and compared to find out the differences. Most of these models are either focused on describing design objects or used to describe the design process. A number of conclusions can be drawn from the analysis and comparison: (1) the FBS model focuses on clarifying the relationships between the design elements; (2) the RFBS model is based on FBS and tries to combine it with System Modelling Language (SysML); (3) the FCBS model tries to combine the functional cells concept with FBS; (4) the FR and the subsequent CFRL model aim to describe the functions in a device through functional modelling; the purpose of SBF model is to support analogical design; (6) the Pahl's prescriptive model of the engineering design process aims to establish the key stages and steps so as to provide guidance on the tasks that need to be carried out; and (7) the Design Rationale emphasises capturing the decision-making with a particular focus on issues, alternatives and arguments. Compared with these models, the RFBSE model emphasises an integrated representation aiming to address both the codification and personalisation aspects of design knowledge. It not only identifies the design objects and their relationships but also considers the know-how and knows-why generated, used and shared throughout the reasoning and problem-solving processes. Mover, the RFBSE model takes a dynamic view on design knowledge, emphasising the evolution of design knowledge throughout a design project or across different projects so as to better address the diversity of designers' knowledge needs.

For the other aspects, few of the previous models consider capturing design context together with design knowledge although it is significant in improving the reuse efficiency. The RFBSE model provides a method to build a systematic framework for organising design knowledge, which can also record the context of generating and using knowledge. Furthermore, the previous models do not provide a method for capturing design knowledge through the design evolution process. Nowadays, new designs are predominantly developed based on existing solutions, by making necessary improvements to meet new customer needs. The RFBSE model has a particular focus on design evolution, providing methods to capture useful design knowledge through the improvement of a design from one stage to another. As such, it can capture the useful knowledge about the particular issues considered, the linkage between existing solution and new requirements and the construction of new solutions. In this way, it can better fulfil designers' knowledge needs particularly in the context of a user-centred knowledge management solution.

#### 7.2.3.2 Application in knowledge representation and reuse

As shown in Table 7.1, each model has its specific way of representing knowledge. The RFBSE model emphasises using graphical diagram-based representation, as it is a visual way of representation which is suitable for organising tacit knowledge. In terms of the ways of organising design knowledge, the previous models do not consider how to integrate knowledge from multiple sources. In the RFBSE model, multi-faceted knowledge has been classified into know-what, know-how, and know-why, and they are integrated to describe a complete piece of knowledge with a rich context. In this way, the knowledge captured is better represented in terms of both the amount of information and the granularity of information, which increases the confidence of reuse. Although existing models can assist design reuse in some ways, few of them can support capturing the knowledge about design objects and put it in a context formed by the process issues. In other words, they only focus a particular aspect, and design knowledge is not captured as an integral part of the engineering design process. On the contrary, the RFBSE model aims to capture design knowledge in a number of key design tasks so as to allow its effective reuse in the later stages of the project or in future projects.

#### 7.2.3.3 Implementation by computer tools

Some of the models listed in Table 7.1 have relevant computer support tools developed for their practical implementation. Most of the tools use diagram-based representation, which shows that it is a good way for the representing the knowledge. The diagram-based representation can give a clear view on what the information is representing as well as identifying the relationships between different pieces of information. In modern product development, knowledge capture and reuse is increasingly conducted within a geographically distributed environment, which entails a collaborative working environment. Different from most of the other tools, the Web-based knowledge management system is designed to be used in the collaborative working environment, and the RFBSE together with the P3 framework are also supporting this aim. Moreover, considering the extendibility of the computer tools, the system guided by the RFBSE model allows users to build firstly a systematic framework for organising design information and knowledge, within which various types of knowledge including formal and tacit knowledge can be added. Beside, details on specific knowledge element can always be added to the framework when necessary. Thus, comparing to the relative fixed representation in other tools, the Web-based knowledge management system has better extendibility.

## 7.3 System Application

### 7.3.1 Overview

A discussed in Chapter 6, a Web-based knowledge management system has been developed for implementing the knowledge capture and reuse tasks. Apart from the system developed, a methodology has been also proposed on how to use the P3 framework, the RFBSE model and the system to capture and represent useful design information and knowledge in a systematic way. With the guidance of this methodology, engineers can record the important information using the Web-based system as well as the knowledge and experience in their mind. In the system, two kinds of elements can be created to structure and represent information and knowledge, namely engineering element and reasoning element. The engineering elements are mainly used for creating a systematic framework which will be used to organise design information and knowledge. This framework provides a context for the reasoning elements created, identifying which design stage an element belongs to, what topic the element is talking about and what issue the element is involved in. The reasoning elements are used to capture and describe design knowledge and experience, including know-what, know-how, and know-why elements. Using these two kinds of elements, useful design knowledge and experience can be captured for reuse with rich contexts related to the design process.

In this chapter, three examples have been chosen to demonstrate how the Web-based knowledge management system developed in this research can be used to capture and organise design information and knowledge for effective reuse. The first example is the intake system design of the racing car project mentioned earlier in this chapter, focusing on how knowledge capture is undertaken as a design process proceeds. The second example is about the casting moulds design of an engine, in which a particular focus is given on capturing useful knowledge through the process of continuously improving a water-jacket mould using simulation analysis. This example is used to explain how to capture and represent useful design knowledge from design evolution. The third example involves a slightly different topic, namely a project on the maintenance of a hydroelectric generator oil head component, which aims to demonstrate the usefulness of the system in non-design tasks such as service and maintenance. Details of these examples are given in the following sections.

### 7.3.2 Knowledge capture alongside the design process

The idea of capturing design knowledge through the design process is to discover and record knowledge as design issues are resolving rather than writing a design report at the end of a project. The intake system design example mentioned in Section 7.2.2 has explained the theoretical support for achieving this task, i.e. using the RFBSE model to capture and represent design knowledge, while this section describes how to implement this task in the Web-based system. As knowledge capture tasks are supposed to be undertaken as the design process proceeds, they will focus on the four main design tasks described in the RFBSE model, i.e. functional decomposition, expected behaviour analysis, structural decomposition and actual behaviour evaluation. In this case, the functional decomposition should be firstly analysed and recorded in the system, with graphical representation and shown in Figure 7.7.

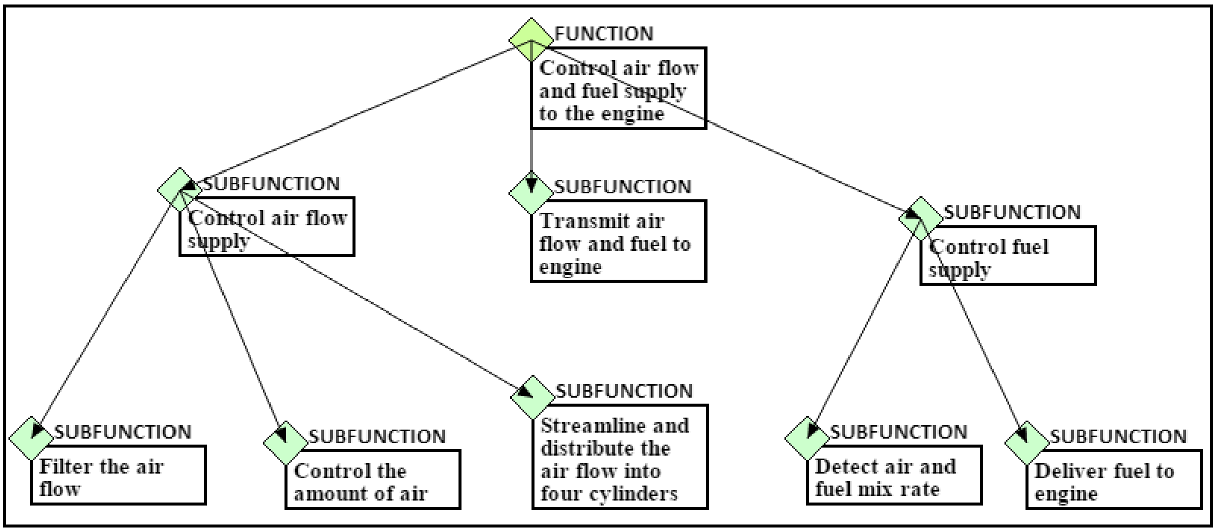


Figure 7.7. Functional decomposition of the intake system

Based on this functional decomposition, the intake system can be divided into 5 components according to the different functions they are to perform, i.e. an air filter, a throttle, an intake body, a transmission, and a fuel supply. These five components are created in knowledge capture GUI of the system, and linked with specific functions they aim to achieve, as shown in Figure 7.8. As the functions are used to meet certain requirements, the relevant requirements should also be recorded and linked to these functions. When creating such a model, the 'Component' element is used to build the basic frame while the 'Function' and 'Requirement' elements are added to specific components. In this process, if any knowledge needs to be recorded, it can be simply created as a node attached to the above elements by selecting an appropriate option (i.e. 'What', 'How' and 'Why') in the middle of the page.

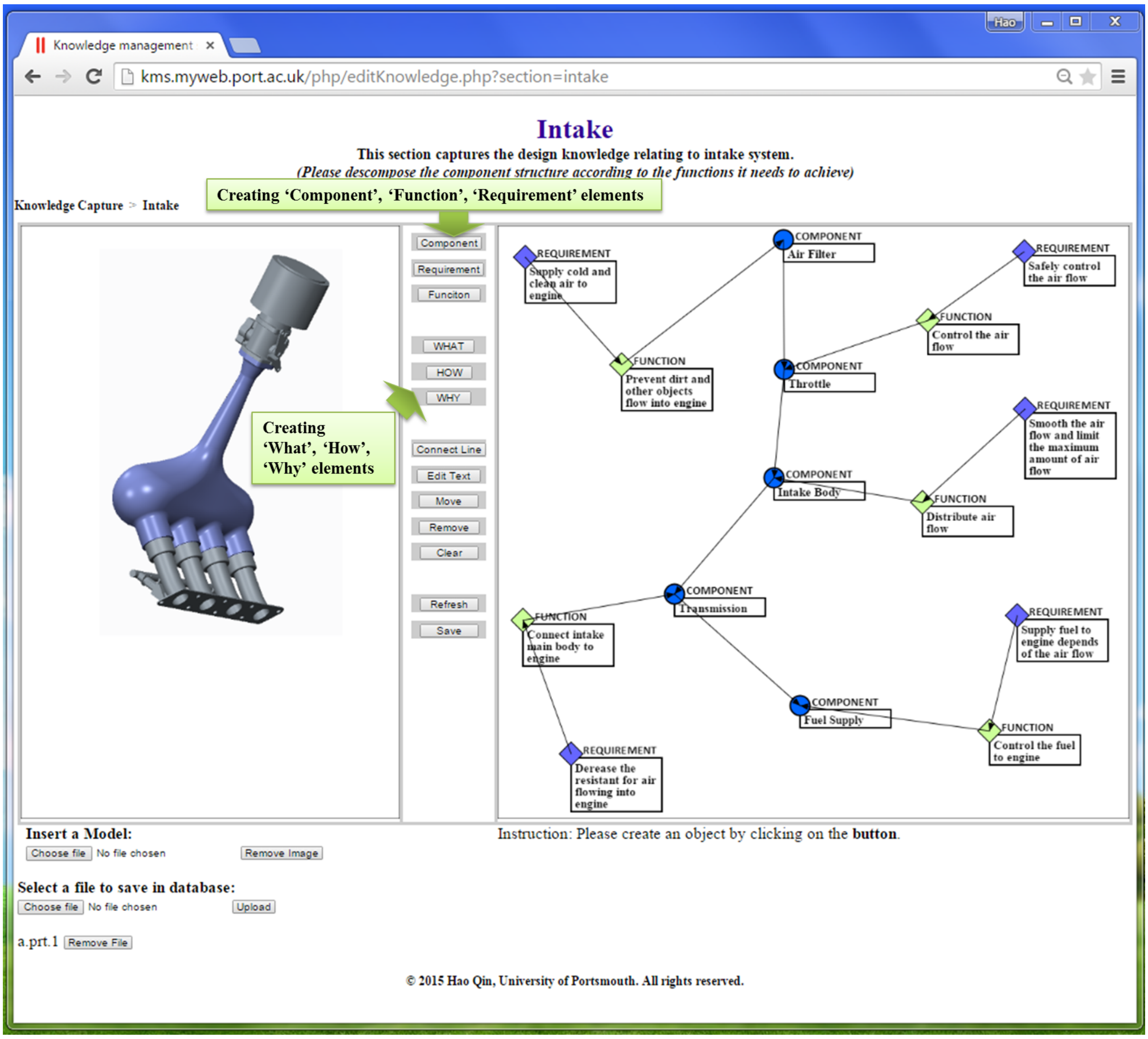


Figure 7.8. Structural decomposition in the system

As 'Component' and 'Function' are the main engineering elements (explained in Section 6.3.2.2) in the canvas, more details can be added to them within a newly opened window by double-clicking on them. For, example, when the 'Throttle Component' in Figure 7.8 is double-clicked, a new knowledge capture GUI will be opened in a new webpage to allow adding details on this component, as shown in Figure 7.9.

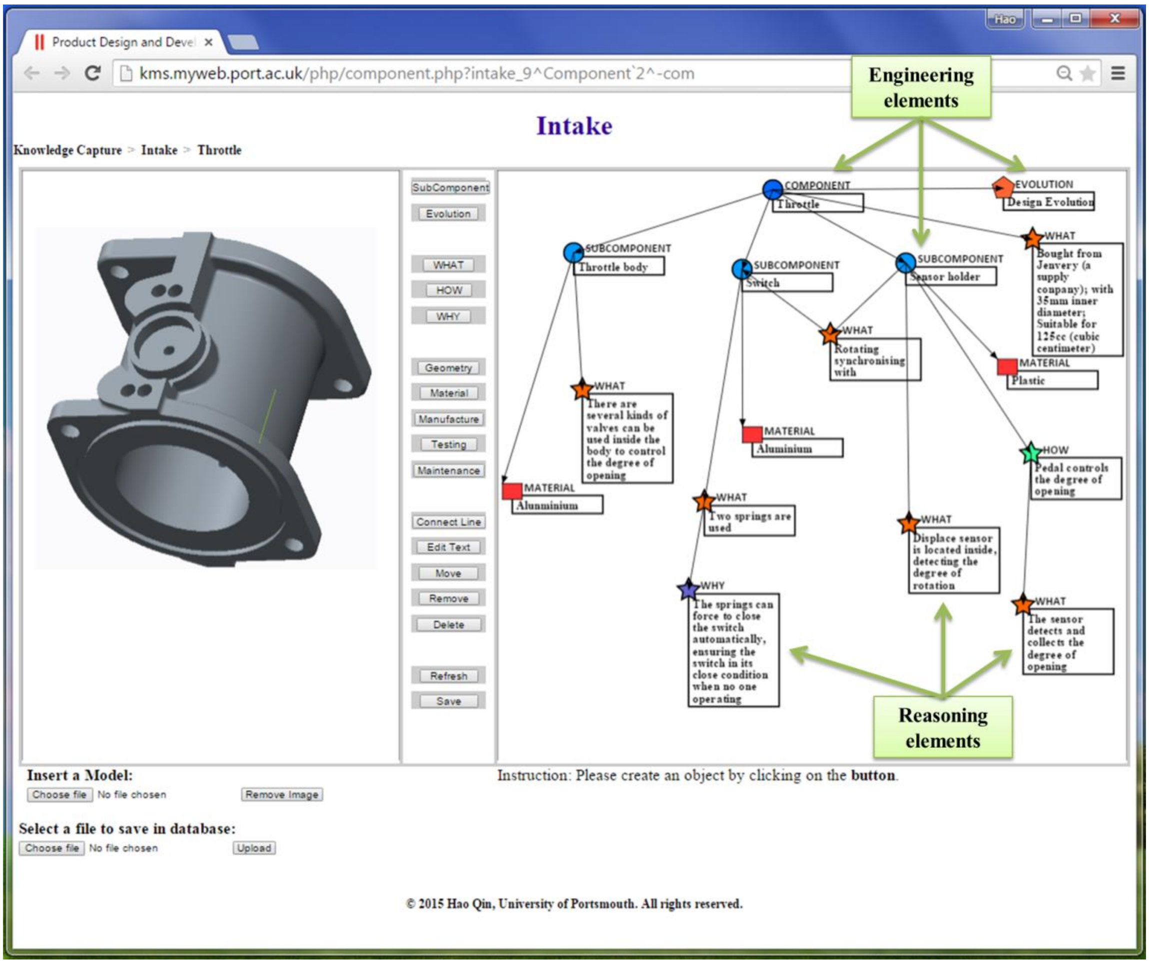


Figure 7.9. Adding more details to the Throttle component

In this newly opened interface, several main engineering elements (for which more details can be added in another window opened when double-clicked on them) and sub-engineering elements (only used for providing description) can be created, including sub-components, evolution, geometry, material, manufacture, testing and maintenance. In this example, three Sub-Components, namely a throttle body, a switch, and a sensor-holder, are created according to the functions they perform. Then, three ‘Material’ elements are created and connected to the three ‘Sub-Component’ elements, providing materials selection information for each sub-component. Also, more details related to the materials selection can be added in another new windows if required. This can also be done to other main engineering elements such as ‘Geometry’, ‘Manufacture’, etc.

More importantly, a range of design knowledge can be captured in this section, using the reasoning elements ‘What’, ‘How’, ‘Why’. Design knowledge (related to a specific engineering element) about what issues to consider, how to approach a problem and why to take a particular consideration or action can be explained and recorded in the form of diagrams created using these reasoning elements. In this way, design knowledge is recorded in a brief textual description and then connected to a specific element, which can provide a clear context for the knowledge recorded.

During the behaviour analysis and evaluation of the intake system, a range of useful design knowledge is generated and it can be organised using another important engineering element ‘Evolution’. This element can be used to track the design changes and improvements made to the components and capture the design knowledge during these processes. In the knowledge capture GUI, the ‘Evolution’ element can be created and linked to a specific ‘Component’ element in order to record its design evolution process as well as capturing useful design knowledge and experience during this process. When an ‘Evolution’ element is created, it can be double-clicked to open a new window where the evolution process can be recorded, as shown in Figure 7.10. In this example, the evolution process of the intake main body is recorded, together with the knowledge generated. There are two part of this evolution process: one is the change from previous design to current design; another one is on improving the design by comparing the actual behaviour of the design to its expected behaviour.

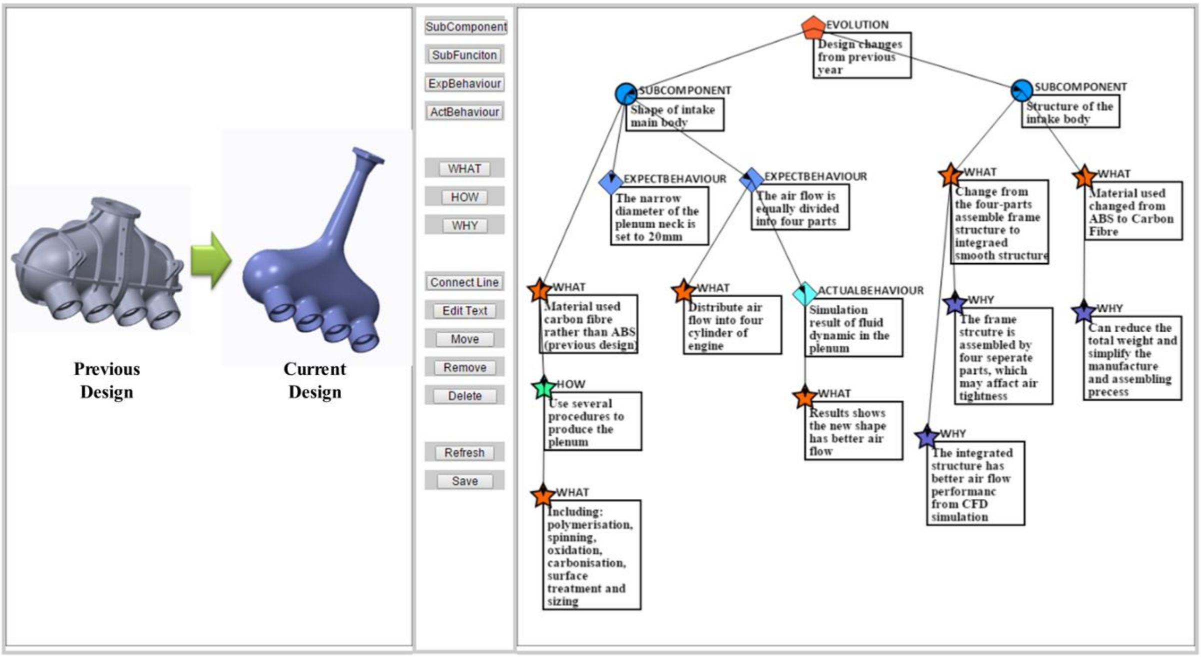


Figure 7.10. Capturing the design evolution process of a component

In this knowledge capture GUI, the left canvas has shown the 3D model of the previous design and current design respectively. On the right canvas, the evolution process and the knowledge generated are recorded by the graphic representation. Different from previous interface, this one has two specific sub engineering elements for this interface, namely an 'Expected Behaviour' element and an 'Actual Behaviour' element. The 'Expected Behaviour' element describes the desired behaviour of the component while the 'Actual Behaviour' element records the behaviour achieved by the current design solution. Generally, there can be several actual behaviours as the design will be modified and improved continuously until a satisfactory one has been achieved. Through this process, several actual behaviours alongside the improvements in design can be recorded, and the design knowledge generated during this process can also be captured. Similarly, the design knowledge generated during this process can be captured using the 'What', 'How, 'Why' reasoning elements.

### 7.3.3 Knowledge capture from design evolution

Within an engineering design project, various tests need to be undertaken to evaluate the behaviours of design solutions by developing prototypes or running simulations, and the results of these tests are usually significant for improving the solutions. To capture the useful knowledge generated in this process, the Web-based knowledge management system provides a means of capturing the information and knowledge during design evolution. A case study which is undertaken in the casting mould design project of an engine production company will focus on how to capture useful knowledge through the design improvement process. The mould design project aims to design a set of moulds for producing a new engine cylinder body. During this design process, previous designs and experience parameters are used as the fundamental parts and then they are improved by adjusting several parameters. These adjustments processes are supported by a Finite Element Analysis (FEA) simulation on the mould designed. The mould fillings are simulated to assess the sand shooting area of the mould. Based on the simulation results, the mould design can be improved gradually. In this case, the knowledge on how to undertake this kind of simulation, and how to improve to the design based on the simulation results is valuable and should be captured for future reuse. Therefore, this case study tries to explain how to capture the useful design knowledge generated through this simulation process by the Web-based knowledge management system.

In order to capture the useful design knowledge through design evolution, a systematic framework should be firstly built according to the RFBSE model to organise the relevant design information and knowledge, which is similar to the previous intake system design example. For instance, the functional analysis and structural decomposition of the mould designs are still required, with examples shown in Figure 7.11 and 7.12.

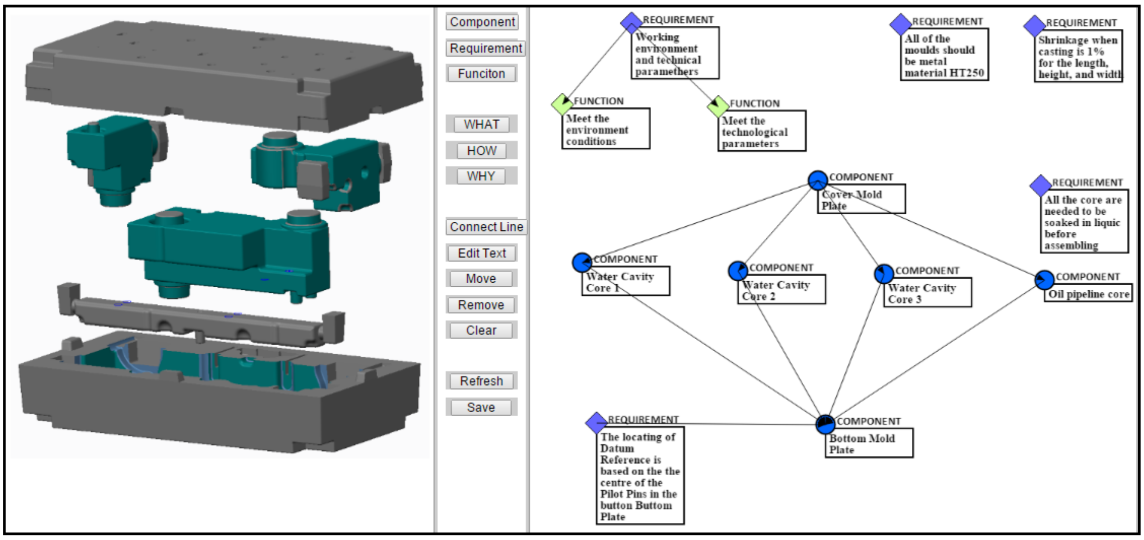


Figure 7.11. Structural decomposition for the mould

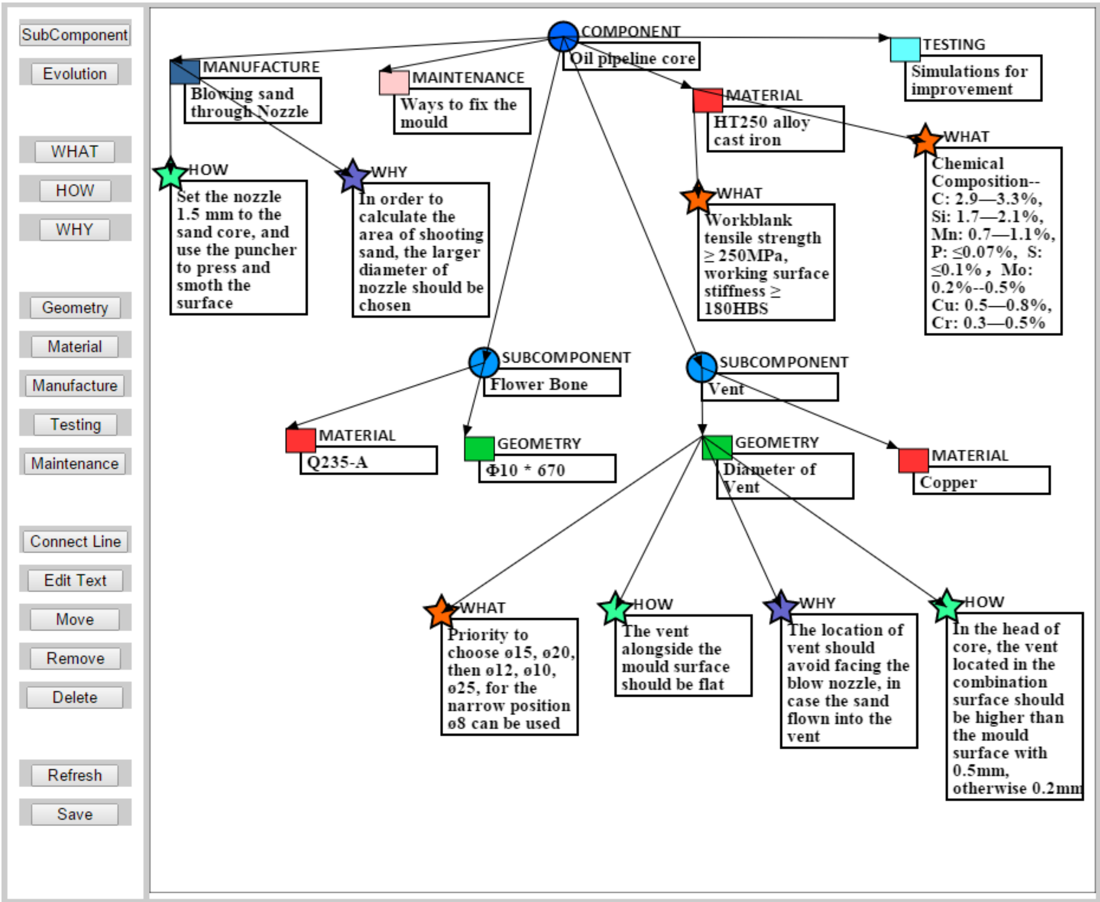


Figure 7.12. Detailed information and knowledge about a mould core

Based on the systematic framework on organising design information and knowledge, the simulation process can be recorded within this framework as well as the useful knowledge generated during this process, as shown in Figure 7.13. This example shows there are seven times of simulations have been done on the water-jacket mould design, which aims to explain how the mould design can be improved based on the simulation results. These simulations are undertaken to check whether the mould design meets certain requirements and how to change specifics parameter to achieve a better design.

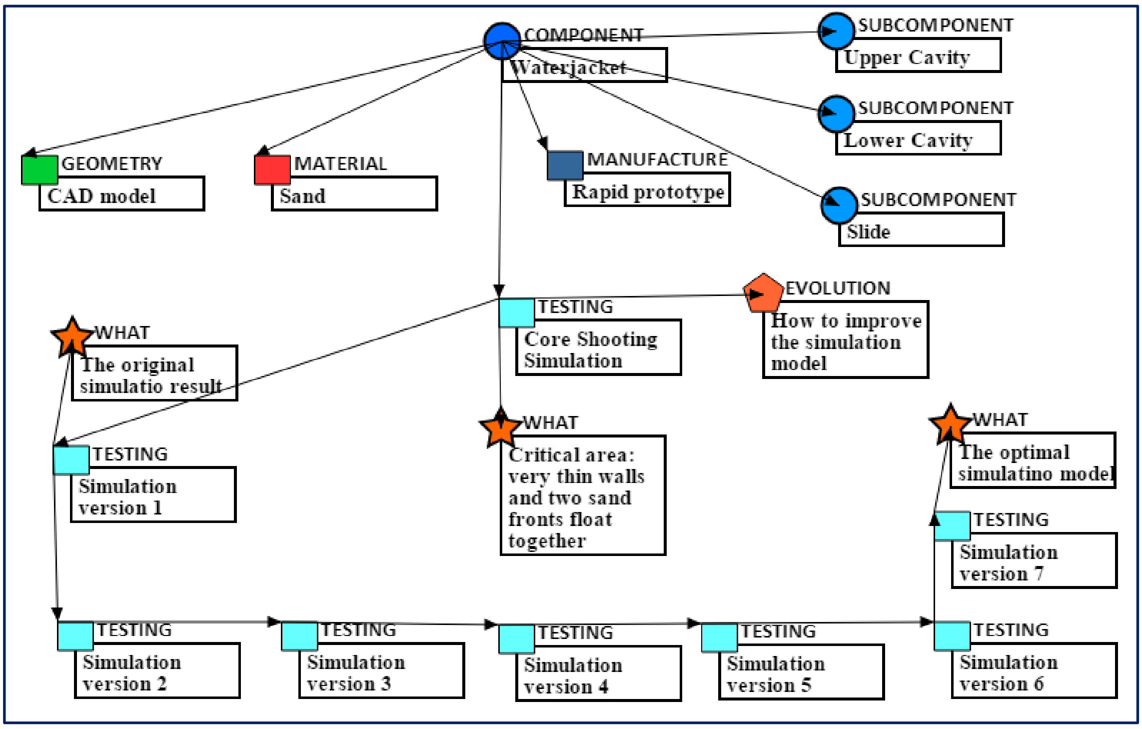


Figure 7.13. Capture design information and knowledge through the simulation process

These simulations of the mould design are used to find out the optimal values for the diameters, numbers and locations of the blow nozzles and vents for the casting mould. These parameters of the blow nozzles and vents have been modified repeatedly based on the simulation results. After seven times' simulations, a final mould design has been obtained by determining the optimal diameters, numbers and locations of the blow nozzles and vents. Through the Web-based knowledge management system, the design knowledge generated and shared during this design evolution process can be captured and recorded using the 'Evolution' element, as shown in Figure 7.14 and 7.15.

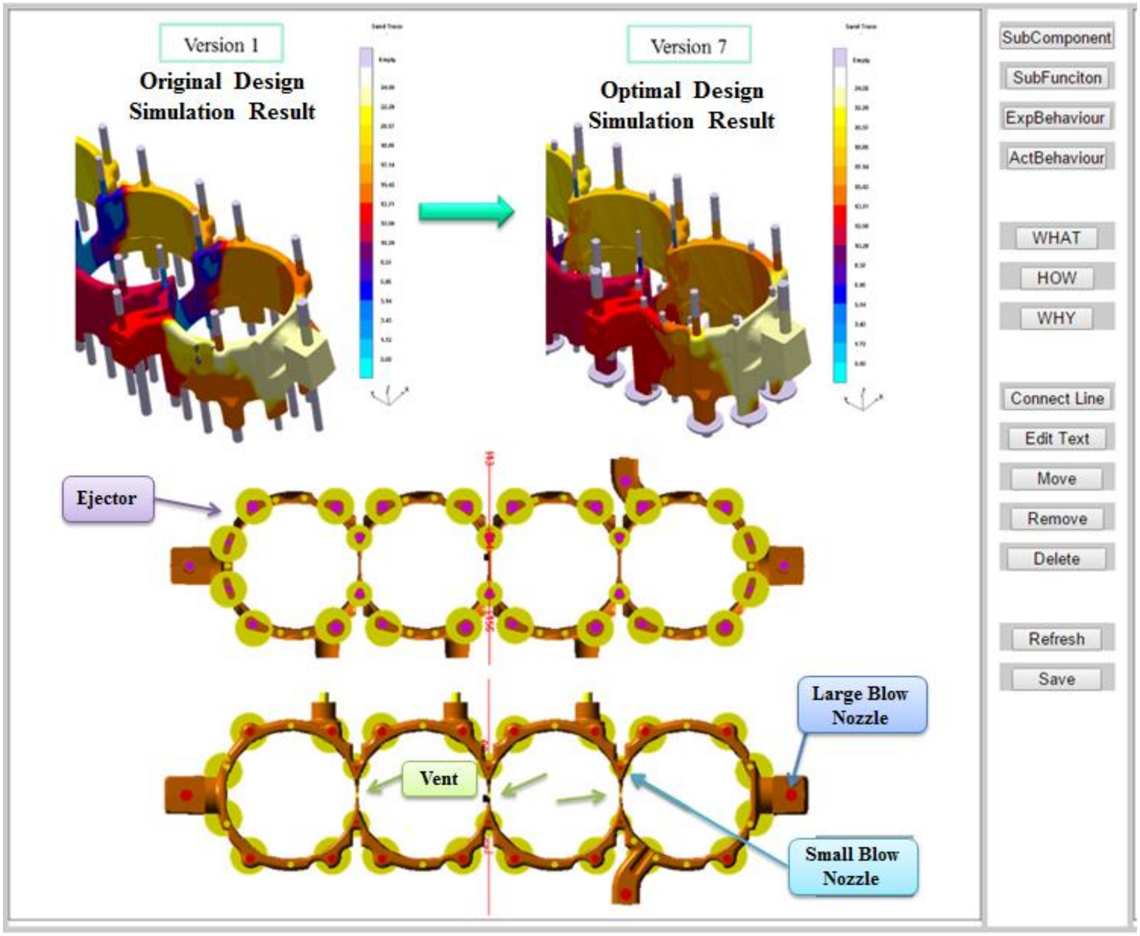


Figure 7.14.The first and the final simulation results of the water-jacket mould

Figure 7.14 shows the left canvas of the knowledge capture GUI on 'Evolution' element of the water-jacket mould design. On this canvas interface, the overview of the simulation results on the first and the finally design is displayed. The top figure tries to highlight the keys point that the brighter the colour in the simulation model the result is better, and the more gently transition of the colour in the critical area of the model the better model is. The another two figures show the top view and bottom view of the simulation model, and the colourful circles and lines added to the figures are used to explain the key issues to be considered, which are used to explain how the mould design has been improved based on the simulation results. The detail description is recorded on the right canvas of the knowledge capture GUI, as shown in the Figure 7.15.

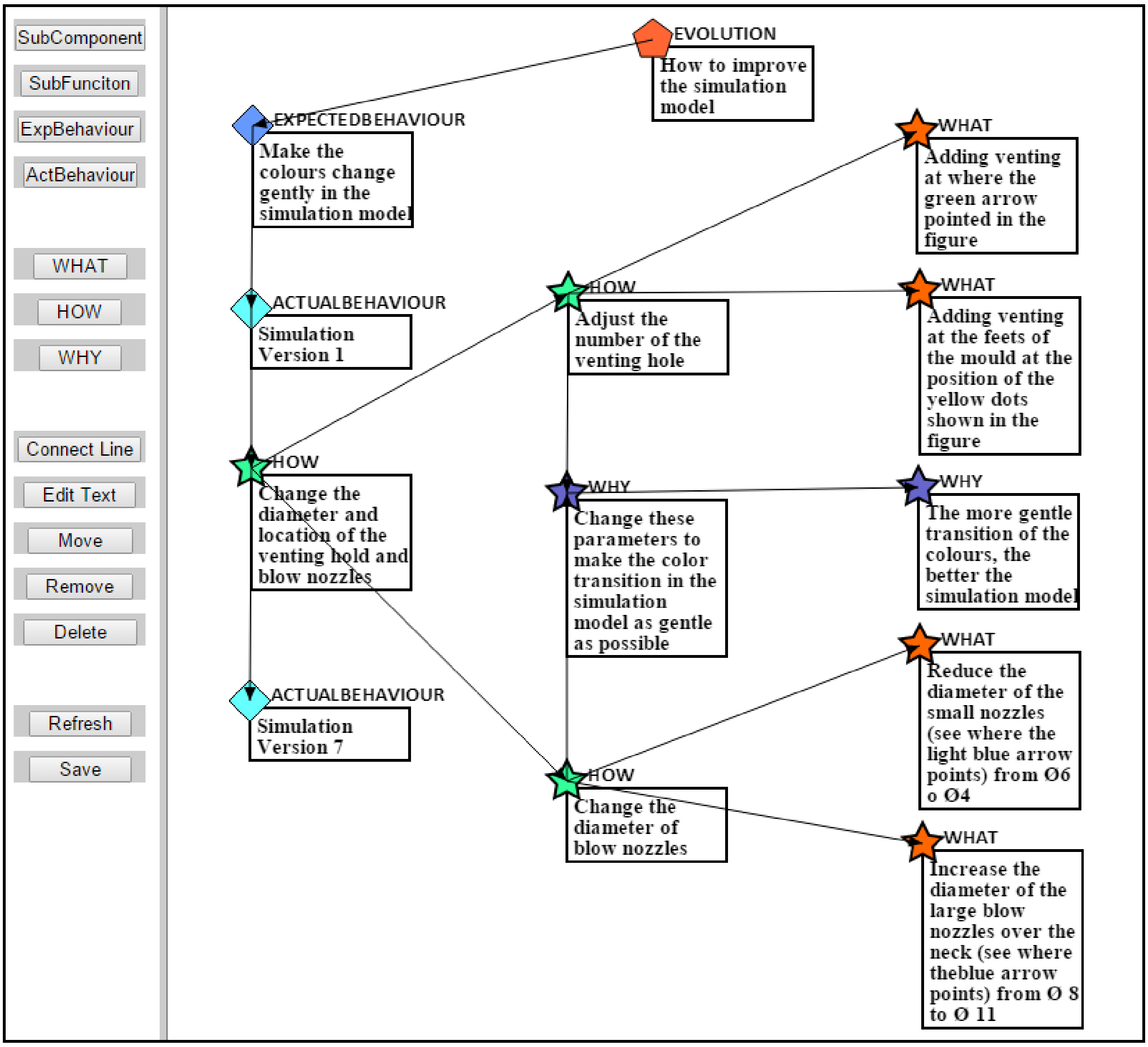


Figure 7.15. Knowledge captured for the design evolution process in the water-jacket mould design

The right canvas interface shown in Figure 7.15 is used to create certain engineering and reasoning elements to explain how to improve the simulation model from the original one to the optimal one. When using reasoning element to demonstrate the issues on the right canvas, such as 'How' reasoning element, it can refers to the figure shown in the left canvas, which can help engineers understand the information and knowledge easily and efficiently. In this way, a range of useful knowledge and experience generated during the design improvement process according to the simulation results can be captured and recorded for future reuse.

### 7.3.4 Knowledge capture for services and maintenance

During the usage of a product, there may be some maintenance undertaken. During the maintenance process, the information on product design, such as engineering drawing, material selection, geometric tolerance, etc., will be useful. Moreover, as the underlying knowledge explains why the artefact has been designed in a certain way, it is highly helpful for the maintenance process. On the other hand, the information and knowledge generated during the maintenance process is also valuable for the improvement of the design in the future, thus they should be captured and recorded for reuse. In this case, the Web-based knowledge management system provides a platform to capture the maintenance information and knowledge, and link to the information and knowledge of the artefact or component when it is firstly designed. A case study on a maintenance project in a hydropower station has been done to show how the Web-based knowledge management system captures and organises the information and knowledge for a maintenance project.

The maintenance tasks are to fix the oil head of a hydroelectric generator and investigate the reason on why it is broken. In this case, the useful design knowledge is generated on how to repair the component and how to avoid this problem happen again. As the original design data and information are used during the maintenance process, the effective way of undertaking the knowledge capture task can still be the method provided by the RFBSE model. Firstly, a systematic framework can be built to combine the original design information of the oil head, including its engineering drawings, materials selection, assemble tolerance, etc., which is captured and organised through the method proposed in RFBSE model, with its structural decomposition shown in Figure 7.16. This also provides a quick access to the specific information during the maintenance project.

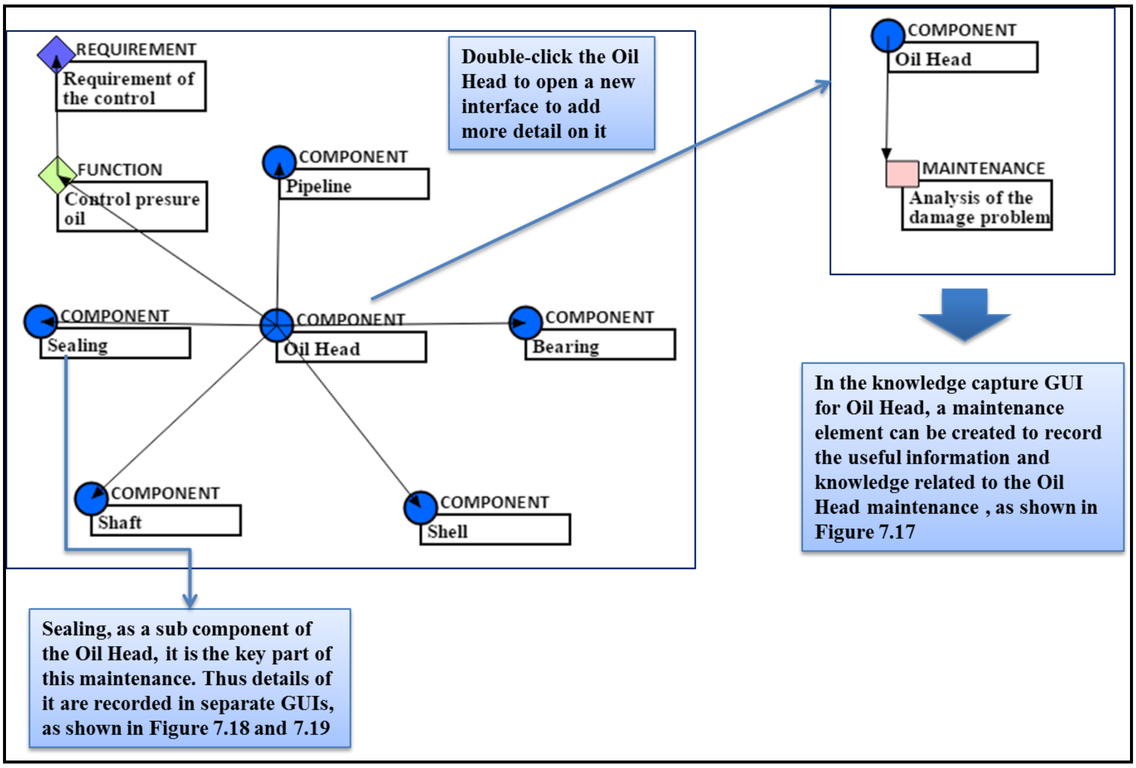


Figure 7.16. Capturing and organising original design information on Oil Head

Based on this framework, the information and knowledge on each maintenance process can be captured specifically to each component of the oil head. For the overall maintenance of the Oil Head, the explanation on the cause of the problem is demonstrated in Figure 7.17. On the right canvas, the ‘What’ reasoning elements are used to describe the key causes step by step, while the ‘How’ and ‘Why’ reasoning elements are used to explains the causes with more details. Also, the important calculation formulas are added and shown on the left canvas, as well as attaching the relevant documents alongside the canvases.

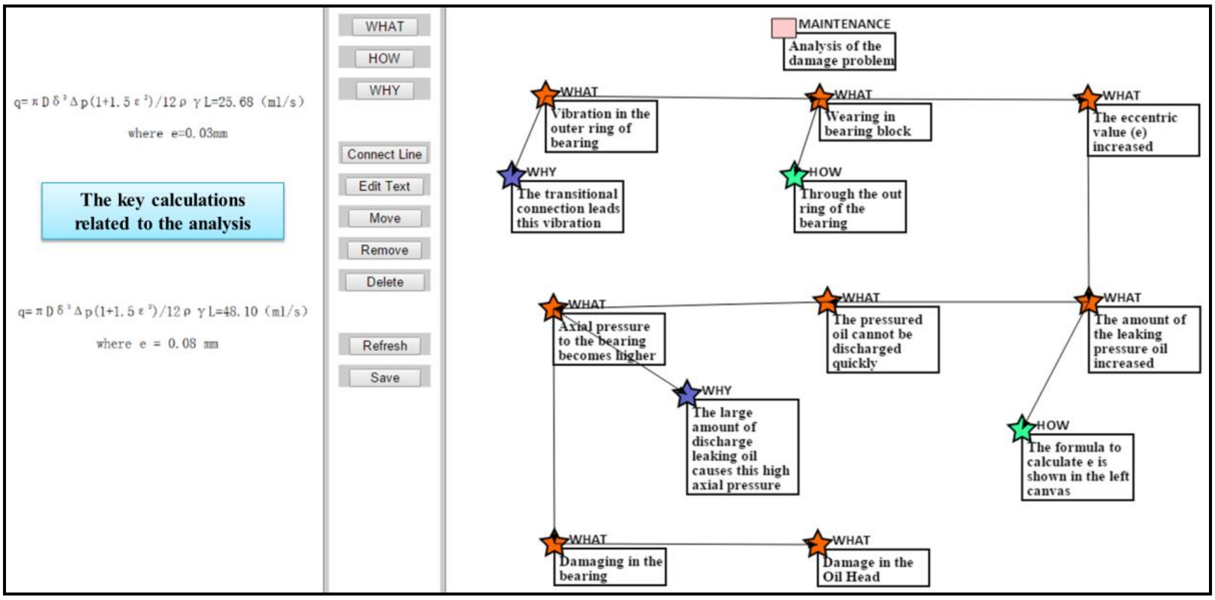


Figure 7.17. The cause of the problem in the Oil Head maintenance project

Moreover, the details of the maintenance for each part of the oil head can also be captured and recorded in specific section. Among them, the sealing component is the key part of this maintenance, as the floating tile of the sealing component caused the problem. Therefore, more details of this component and the knowledge generated during the analysis of the problem has been captured and recorded in the system, as shown in Figure 7.18 and 7.19. Firstly, on the knowledge capture GUI shown in Figure 7.18, the key issues are recorded by several reasoning elements, and a ‘Maintenance’ engineering element is created to capture the information and knowledge on maintenance process of the ‘Floating Tile’. As the ‘Floating Tile’ is the key component that causes the problem in the oil head, the maintenance process of if should be analysed in details and reason of the problem should be explained. In this case, the details on the maintenance process are described on another canvas interface window, as shown in Figure 7.19.

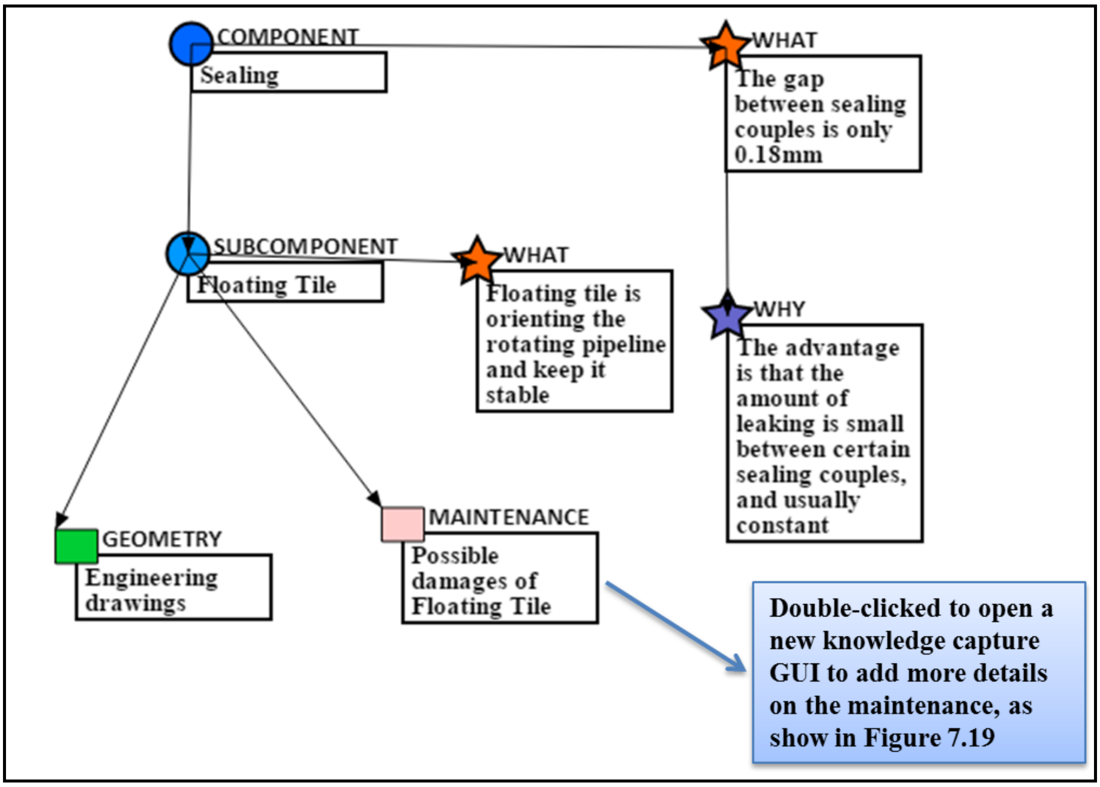


Figure 7.18. Information and knowledge on the Oil Head Sealing

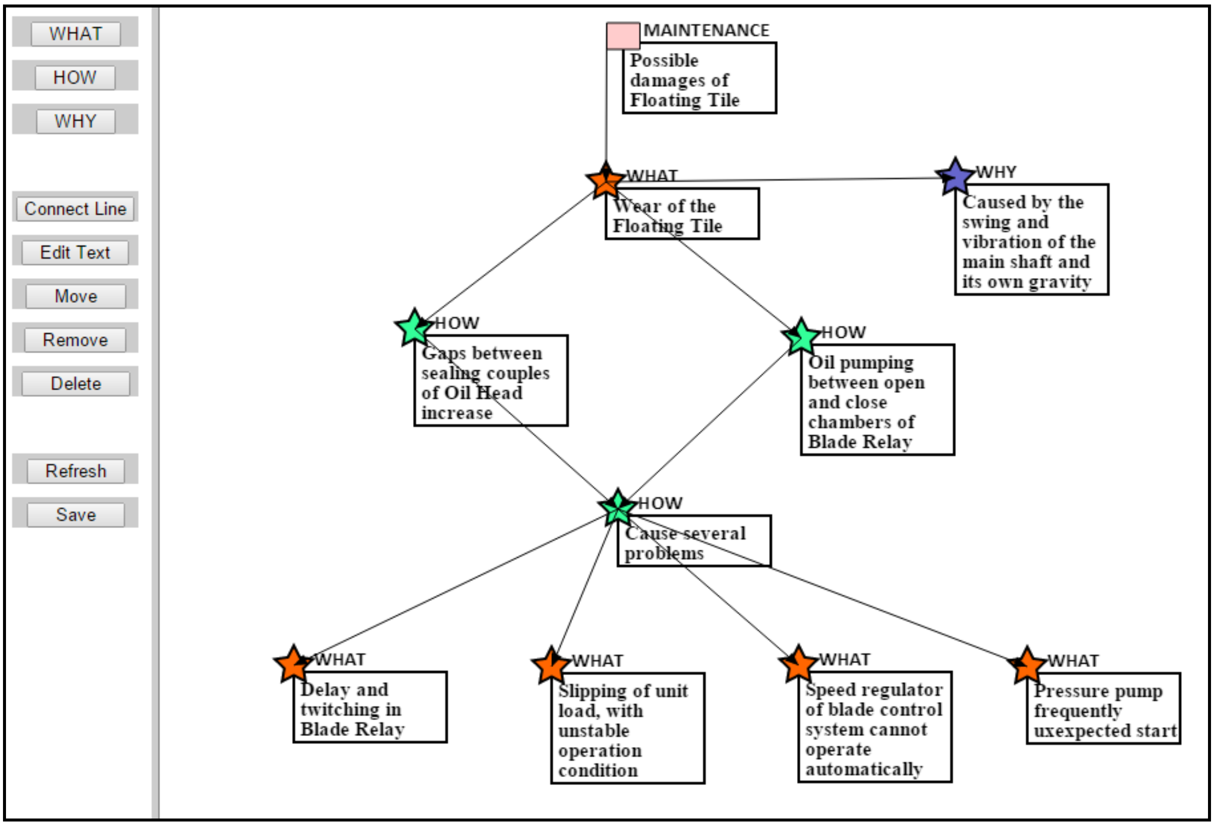


Figure 7.19. Information and knowledge on the maintenance of the Oil Head Sealing

Similarly, in this window for capturing maintenance information and knowledge, the 'What', 'How' and 'Why' reasoning elements are generated and used to explain the issues during the maintenance process, with supporting information can be added on the left canvas or upload to the database as attachments.

## 7.4 Discussion

Through applying the RFBSE model to real engineering design projects and comparing it with some established knowledge models, several advantages of the RFBSE model and the system have been identified. Firstly, the RFBSE model is an integrated model which not only describes design objects in an engineering design project but also captures useful knowledge about how to carry out tasks for the key design stages of the design process. In this case, the model can integrate both formal and tacit knowledge together within a systematic framework that can support capturing knowledge as part of the design process. Secondly, the model captures both design context and knowledge context. The design context is obtained through the framework built based on the four main design tasks proposed in the model while the knowledge context is captured by classifying design knowledge into know-what, know-how and know-why and then attaching each piece of knowledge to specific elements in the framework. Thirdly, the RFBSE model provides a way to capture and represent design knowledge with finer granularity of information, i.e. in the form of diagram-based elements describing know-what, know-how and know-why within a clear hierarchy of knowledge context. In this way, a piece of tacit knowledge can be recorded and represented with detailed content and clarified context, which is highly useful for subsequent retrieval and reuse. Finally, the RFBSE model takes account of the changes that may happen to both design objects and knowledge elements, i.e. evolution. In this work, the term evolution involves two aspects, namely capture of the useful knowledge during design evolution and evolution of knowledge structure and content as time goes by (in a project or across different projects). The Evolution element has been introduced in the RFBSE model to precisely address these aspects so that useful knowledge can be captured to explain the underlying principles behind the changes and improvements whilst its content can be updated as a design project proceeds.

The Web-based knowledge management system has been shown and explained to the engineers from the projects used in the case studies. The general feedbacks received are highly positive, which can be mainly divided into three parts, i.e. application in engineering problems, knowledge capture and representation, and collaborative working. In terms of application in engineering problems, the system can be applied in various situations, including a complete design process, design improvements based on testing and simulation, and non-design projects related to services and maintenance. It can provide useful information and knowledge to the engineers in an effective and efficient way. In this case, engineers can record their knowledge and experience in the system as a project proceeds rather than writing a long report at the end of the project. In terms of knowledge capture, the graphical representation is user friendly and proved to be popular for the engineers. They consider it as an easier way to capture, organise and reuse design information and knowledge. Also, the method provided by the RFBSE model can guide how to organise design knowledge in their mind and record it in the system more efficiently. Moreover, the systematic structure of organising information and knowledge can help novice engineers to find out what kinds of information and knowledge they really require and provide guidance to them when they need to acquire information and knowledge. In terms of collaborative working, the Web-based system allows the engineers to work in a distributed working environment in which useful design information and knowledge is generated and shared through collaborative working. They can use the system from any place where they have access to the Internet and can work on same section in the system simultaneously. Besides, the system supports the engineers to access the information and knowledge from other stages and as such people working on different tasks and across different stages can collaborate on the system. For example, within the system, an engineer working on the maintenance project can refer to the information and knowledge recorded from the original design process to assist their current maintenance tasks.

## 7.5 Summary

This chapter provides a demonstration of how to apply both the RFBSE model and the Web-based knowledge management system in engineering design projects. The RFBSE model can be used to guide the engineers in the projects on how to capture and organise design information and knowledge throughout a complete design process in particular the tacit knowledge in their mind. The Web-based knowledge management system provides a methodology and computational support for design engineers to undertake knowledge capture tasks. It can not only enable capturing knowledge from design tasks but also provide support for other stages of a project such as testing and maintenance. Through the evaluation of the model and the application of the system in several engineering design projects, they have been proved to be useful in helping engineers to capture, organise and reuse their design knowledge and experience generated during engineering design projects.

# Chapter 8

# Conclusion and Future Work

## 8.1 Thesis Review

The thesis has explored a systematic method for capturing, representing and reusing useful design knowledge and experience through the design process within a collaborative working environment. This study has three main parts, namely the requirement analysis on knowledge capture and reuse, the development of theoretical methods and models, and the implementation of a knowledge management system embodying the methods and models. They have been demonstrated in the above chapters, and an overall review of the thesis is concluded in the following paragraphs.

In Chapter 1, the background, motivations and objectives of the research are discussed. The purpose of the thesis is to find out an effective way of capturing engineering designers' knowledge and experience throughout the design process. In order to achieve this goal, several objectives have been identified. Firstly, a survey study has been conducted to find out the information needs and information-seeking behaviours of new generation of engineers in a collaborative working environment. Then, the P3 framework is proposed to build a systematic framework for organising the information and knowledge within an engineering design project with a particular focus on the sharing and reusing of these information and knowledge in a collaborative working environment, whilst the RFBSE model is proposed to provides the detail methods to capture and represent the integrated knowledge on both design objects and design processes. Based on the results of the survey study and supported by the P3 framework and the RFBSE model, a Web-based knowledge management system has been designed and developed for the practical implementation of the proposed models and methodology. Lastly, the RFBSE model and the Web-based knowledge management system are applied to several engineering design projects to demonstrate and evaluate the proposed methods and on this basis to make further improvements.

Before the main sections of the thesis, a literature review of related work is done in Chapter 2. This chapter reviews the previous research in the area of knowledge management for engineering design and identifies the key issues in this research area. Specifically, the review first discusses what knowledge management for engineering design is and its importance, and carries on by giving an explanation of the definitions of data, information and knowledge, as well as their differences and relationships. Also, the literature on investigating engineering designers' information needs and information-seeking behaviours during engineering design projects is reviewed to identify the areas of support that knowledge management research can provide. Previous work on the methods for knowledge representation and reuse is thus reviewed and discussed along with the possible computer support tools for their implementations, in order to identify the gaps to be filled in this research. Besides, reviews have been undertaken on the knowledge management within a collaborative working environment, which identifies its importance and provides the possible methods.

Chapter 3 details the methodology for undertaking this research. As there are three main parts of the research, i.e. survey study, knowledge models, and knowledge management system, the specific methods for each part are different and need to be justified separately. However, the combination of these three parts can be regarded as a complete methodology for the whole research project. The survey study is designed to identify engineers' information needs in a new context in which collaboration and information play an important role. The development of knowledge categorisation framework and knowledge representation model aims to create a systematic structure that can be used to describe the useful knowledge for the new context based on the results of the survey as well as a review of existing methods. All the methods are demonstrated and analysed by implementing them in a prototype knowledge management system to prove their feasibilities, evaluate their performances and obtain insights into the technological issues in the development of a new generation knowledge management systems.

The survey study is described in Chapter 4. This chapter begins with a discussion on the issues that necessitate this study. Then, the survey design and together with how to deliver the study in an engineering design project is detailed. There are two parts of the study, namely an informal interview and a questionnaire. The interview was first undertaken in order to gather some basic information for questionnaire design. Next, the questionnaire was delivered to the engineering design project team members. The data obtained from the questionnaire are analysed to determine the information needs and information-seeking behaviours of next-generation engineers. The findings of this analysis are used in the following parts of the research.

With the results and findings obtained through the literature view and survey study, two models are proposed in Chapter 5. The first one is the Product-Process-Project framework, which is a knowledge framework aiming to classify and organise the information and knowledge which is important for delivering an engineering design project. It has three sub models, namely Product model, Process model and Project model, which are specific for the organising information and knowledge in three specific areas. The second one is the Requirement-Function-Behaviour-Structure-Evolution knowledge representation model, which focuses on capturing, representing and reusing design knowledge from the design objects and activities during the design process. It uses the five elements mentioned in its name to build specific contexts for capturing useful design knowledge through four main design tasks, i.e. functional decomposition, expected behaviour analysis, structural decomposition and actual behaviour evaluation. Through the methods provided by the RFBSE model, the tacit knowledge can be integrated with formal knowledge within a clarified context for future reuse. These two models are used to guide the design and development of the prototype system in Chapter 6.

A Web-based knowledge management system has been designed and developed in this research, as described in Chapter 6. This chapter starts with the system architecture design, identifying three layers for the system, namely the user interface, application and repository layers. Then, the details on how to develop the system with enabling technologies are given. As a Web-based system, it uses the state-of-the-art Web programming technologies including HTML5, CSS 3, JavaScript, PHP and MySQL, to achieve better information display and operation. The idea of the system is a knowledge-centred solution which concentrates on capturing and representing design knowledge and uses this knowledge to provide rich contexts for relevant design data and information. In this sense, the system effectively integrates tacit and explicit knowledge using more interactive and friendly interfaces enabled the state-of-the-art technologies and can thus be regarded as a step towards the next-generation knowledge management system.

In Chapter 7, several case studies have been undertaken for applying both the RFBSE model and the Web-based knowledge management system. An intake system design has been used as an example to demonstrate how the RFBSE model can be used to capture and represent design knowledge and experience during a design process. For the application of the system, three engineering projects have been chosen as examples. The intake system design is also used in this case to show the effectiveness of the system in capturing and organising integrated information and knowledge through design process. Also, another example of an engine water-jacket mould design has been used to demonstrate how to use the system to capture useful knowledge through the design evolution process driven by testing and simulation results. Besides, a maintenance project in an oil head of a hydroelectric generator has been used to identify how the system can support capturing and organising information and knowledge for the maintenance and services processes. Evaluations have also been undertaken for both the model and the system: for the model, it has been compared with several previous models to evaluate its usefulness; for the system, the system has been demonstrated and tested in the engineering projects mentioned above for the engineers' feedback, based on which the system has been further improved.

The main conclusions are drawn in Chapter 8. This chapter firstly reviews the whole thesis, and then identifies the main findings of this research and makes several suggestions for future works.

## 8.2 Main Findings and Contributions

The main findings and contributions come from the way of achieving the research objectives. The findings and contributions of this research can be summarised in three areas, namely findings obtained from the survey study, development and evaluation of the knowledge models, and the design and implementation of a prototypical knowledge management system. They are described with details in the following sections.

### 8.2.1 Main findings from the survey study

Through the survey study, the information needs and information-seeking behaviours of the next-generation of engineering designers have been identified and analysed. During an engineering design project, the information needs of engineers will evolve, from general to specific. This is more evident for novice designers. At the beginning of the project, they need to know the background of project and its basic information in order to start their tasks. This kind of information is quite general and should be structured in order to be better understood especially for novice engineers. As the project proceeds, engineers begin to require information related to specific issues on reasoning, problem-solving and decision-making. In this case, the underlying design knowledge about problem-solving strategies and considerations is what the engineers actually need as it explains the usefulness and contexts of specific design data and information and guides how to carry out certain tasks and use the data and information. The survey results also show that a new generation of engineers prefer to use new information technologies to support information accessing and sharing especially within a collaborative working environment. Also, from the survey results, the key functionalities for the Web-based knowledge management system have been identified, which reveals the trends for the development of useful computer support tools on supporting knowledge capture and reuse in the near future.

### 8.2.2 Knowledge models

There are two models proposed in this research, namely the P3 framework and the RFBSE model. The P3 model is used to integrate all the aspects within an engineering design project in order to build a systematic framework which creates the context for knowledge capture and reuse. It includes three sub models, namely a Product model, a Process model and a Project model, which correspond to three different areas within an engineering design project. Specifically, the Product model considers the information and knowledge related to design objects; the Process model describes key issues in problem solving and clarifies information flow in the project; and the Project model deals with the supporting information and knowledge related to project management. The overall function of the P3 model is to identify the key elements of a design projects (e.g. components, issues and tasks) within a collaborative working environment and create a systematic framework to provide the context of capturing useful information and knowledge for future reuse.

The RFBSE model has provided a method to capture design knowledge and experience from design objects and design processes. It has identified the five keys elements within the design generation and evaluation process, namely requirement, function, behaviour, structure and evolution, together with four important design tasks, namely functional decomposition, expected behaviour analysis, structural decomposition and actual behaviour evaluation. Through these elements and tasks, the model clarifies when and where the useful design knowledge and experience may be generated as well as how to capture and represent different pieces of knowledge in a systematic way for reuse, and creates the context for the design knowledge captured. In this way, product knowledge about design objects and process knowledge about problem-solving and decision-making processes can be captured together, and the knowledge capture can be undertaken alongside the design process. Also, the model classifies the knowledge into know-what, know-how and know-why, which is beneficial for capturing and recording tacit knowledge while enabling the integration of this tacit knowledge with formal knowledge in a systematic framework. Besides, the model has emphasised the importance of capturing design knowledge through design evolution, and provided a method to capture useful knowledge from this evolution process.

The P3 framework and the RFBSE model are proposed to work together in providing the guidance on how to capture the useful design knowledge alongside the design process, which provides ideas for the implantation of next-generation of knowledge management system.

### 8.2.3 Web-based knowledge management system

The Web-based knowledge management system designed and developed in this research can not only be used to organise and manage design data and information but also serve the purpose of capturing design knowledge and experience through the whole process of an engineering design project. The system uses a knowledge-centred concept, i.e. concentrating on capturing useful design knowledge and then combing useful data and information related to it. Moreover, the system applies model-based representation that uses the RFBSE model to guide the knowledge capture and representation, which allows the knowledge capture tasks can be undertaken alongside the design process. Besides, the system is built within the Web environment, aiming to support collaborative working whilst enabling more effective and efficient accessing and sharing of information and knowledge. The graphical representation of knowledge elements provided by the system can help users easily understand and reuse design information and knowledge through the visualisation of clear hierarchy and relationship. Also, fine information granularity achieved by the knowledge representation is beneficial for information navigation control, allowing engineers to switch between general and detailed information effectively. Therefore, the system provides new ideas and technologies that can be incorporated to the development of the next-generation of knowledge management systems.

## 8.3 Suggestions for Future Work

This research has several aspects that can be further improved, which are discussed as potential future work. Firstly, the P3 framework and the RFBSE model are proposed based on mechanical engineering design problems, thus the elements of these models may need to change when used across different sectors. For instance, the Product model of the P3 framework will be different in architecture, and the definition of the Behaviour and Structure elements in the RFBSE model should also be various in the medical area. In this case, future work can be undertaken to analyse and improve the models proposed in this research for their applications in others sectors. For the Web-based knowledge management system, some functionality has not been fully explored in details in this research due to the time limitation. This includes the individual working space, intelligent recommendation, knowledge retrieval, and 3D model representation and operation. These aspects can also be explored to further improve the system in future work.

### 8.3.1 Knowledge models

The P3 framework and the RFBSE model are proposed in the engineering design field, especially for mechanical design. However, their theories and methods can be extended and applied to other situations where knowledge and experience of problem solving plays significant roles. Thus, more work can be done on analysing how to adjust the models in order to apply them in other sectors.

Among the three sub models of the P3 framework, the Product model and Process model are highly dependent on what kinds of projects they are dealing with. Specifically, the consideration on the decomposition of an artefact or component may be varying in different areas, e.g. architecture or medicine. In this case, analysis work should be undertaken on how to effectively use the Product model in different areas. Similarly, the information flow described in the Process model is based on the classical engineering design process, which is more suitable for mechanical and electrical products. For the other sectors, some processes in the Process model such as design and manufacture should be changed to meet specific requirements.

For the RFBSE model, the elements may need to be adjusted in order to apply it in other areas. The function, behaviour, structure elements and the four main design tasks described in the model are proposed based on mechanical engineering design. As such, when using the RFBSE model to capture useful knowledge and experience in other areas, such as medicine, these elements may change to other domain specific terms. However, the core idea and the methods proposed in the RFBSE model can still be used to undertake knowledge capturing and representing tasks. Therefore, future work can be undertaken on how to adjust the RFBSE in order to apply it in different areas.

### 8.3.2 Individual working space

The research has proposed the idea of using individual working spaces and added it to the system architecture of the Web-based knowledge management system. Also, an Individual working space GUI has be created for its implement. However, the details of this GUI have not been fully implemented while more research is needed to study how design contexts can be described in these spaces and how to supply relevant knowledge to designers as they are working a specific design task.

Individual working space is a useful method to organise engineers' personal information and knowledge to provide support for their knowledge capture and reuse. First of all, it is an area which gathers all the information and knowledge regarding to specific users of the system. Engineer can access to this space through a separate GUI. Within this space, users can have an overview on what kinds of information and resource they have within the project, as well as their current status within the whole project. On the other hand, the Web-based knowledge management system can recognise the current working stage of the users and on this basis suggests relevant information that may helpful to them. In this case, the individual working space provides useful contexts of the users, which provides support for automatic recommendation of information, which is explained in the next section. Therefore, future work can also be undertaken on detailing the individual working space GUI of the Web-based knowledge management system.

### 8.3.3 Intelligent recommendation

With the highly developed information and computer technologies, more advanced functionality can be achieved in the Web-based distributed environment. Intelligent recommendation is a technology that can provide suggestions to users according to the information they are accessing, recording or sharing. It will be a useful functionality if this technology can be used in the Web-based knowledge management system. As mentioned before, the individual working space can gather users' information that provides rich contexts of working such as what information has been created and used. Based on these predicable contexts, intelligent recommendation can find out the information that the users may be of interest and deliver this information to them at the right time. Therefore, future work can be undertaken to define various contexts and exploring the technologies for pushing information for the Web-based knowledge management system.

### 8.3.4 Knowledge Retrieval

More future work can also be undertaken on the system's knowledge retrieval functionality. As the knowledge recorded in the research is in the form of What, How and Why elements. The knowledge retrieval GUI can perform the function of searching for relevant information from the database and assembles different pieces of information into a complete piece of information which explains the underlying knowledge. Compared with traditional searching methods, this knowledge retrieval can find out the exact information and knowledge users need on a knowledge element, e.g. a component structure, a machining process, or a material selection. In order to achieve this functionality, future work can be undertaken on advanced retrieval algorithms, relationships construction and search strategies.

### 8.3.5 3D CAD model representation and operation

For the graphical representation of the Web-based knowledge management system, more future work can be done on 3D model representation. The idea is to use 3D CAD model displayed alongside the relevant design knowledge captured. This 3D model is not only used for displaying purpose, but also used to allow attaching small pieces of information onto it. Users can create a knowledge element on the surface of the 3D model by creating a colourful dot on the specific area which can be double-clicked to open a new GUI for recording more detailed information. In this way, users can easily access useful information and knowledge when they are viewing the 3D CAD models. Therefore, future work can be undertaken on exploring the 3D representation technologies in the Web environment and incorporating them into the Web-based knowledge management system.

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# Appendix A

# Publications

1. Qin, H., Wang, H., and Liu, Y. (2015). An integrated RFBSE model for managing and reusing engineering design knowledge. In: *Proceedings of the 20$^{th}$ International Conference on Engineering Design (ICED 15).* Milan, Italy.

2. Qin, H., Wang, H., Wiltshire, D., and Wang, Q. (2013). A knowledge model for automotive engineering design. In: *Proceedings of the 19$^{th}$ International Conference on Engineering Design (ICED13).* Seoul, South Korea.

3. Qin, H., Wang, H., and Zhao, Y. (2013). A knowledge model for sustainable automotive engineering design. In: *Proceedings of International Conference on Design and Manufacture for Sustainable Development (ICDMSD 2013)*. Hangzhou, China.

4. Qin. H., Wang, H. and Johnson, A. (2015). Understanding engineering designers' information needs: Implications for an integrated and collaborative knowledge management system. *Journal of the American Society for Information Science and Technology*. (Submitted)

5. Qin. H., Wang, H. and Johnson, A. (2015). A RFBSE model for capturing useful experience and knowledge from the design process. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing.* (Submitted)

6. Wang, H., Qin, H., and Zhang, H. (2013). Managing engineering analysis knowledge. In: *Proceedings of IEEE International Conference on Computer Supported Cooperative Work in Design (CSCWD 2013).* Whistler, BC, Canada.

7. Zhao, W., Qin, H. and Wang, H. (2014). A Web-based system for reusing automotive engineering design knowledge. *Proceedings of the 14th International Conference on Tools and Methods of Competitive Engineering (TMCE 2014).* Budapest, Hungary.

8. Mochammad, F., Wang, H., Qin, H., and Liu, Y. (2015). Digital repository for design knowledge reuse. In: *Proceedings of the 20th International Conference on Engineering Design (ICED 15).* Milan, Italy.

# Appendix B

# Questionnaire of the Survey Study

## A Survey on the requirements for an Information System to assist information management and design re-use in the Formula Student Project

**(You can choose multiple answers for the questions)**

**Many thanks for your effort in completing this survey.**

**Please return the completed survey by emailing to hao.qin@port.ac.uk**

**by 15/03/2013.**

| | | | |
|---|---|---|---|
| **Name** | | **Grade** | |
| **Subject in the University** | | | |
| **Time since you have joined the team (month, year)** | | | |
| **Section you are working in** | | | |

**1. What is your daily task in the Formula Student Project _____**

A. Drawing and modelling
B. Simulation and analysis
C. Product/part requirement analysis
D. System breakdown and functional analysis
E. Material selection
F. Manufacturing
G. Data and information management
H. Others ___________

**2. What do you want to know about the project when you first joined the project _____**

A. Previous design(s)
B. The design and manufacturing processes
C. Solutions for specific issues/problems in the past
D. Project background
E. Specification of the design task
F. Legislation and official regulation
G. Relevant patents, standards and technologies
H. Administrative process of the project
I. Budget and resources
J. Requirement for design & manufacture a product/part
K. What issues to consider and when to consider them
L. Information on material selection and manufacturing methods
M. Others ___________

**3. Please choose three from the options in Question 2 which you think are most important and rank them in descending order in terms of importance**

_____ > _____ > _____

**4. What do you want to know at the present stage _____**

A. Previous design(s)
B. The design and manufacturing processes
C. Solutions for specific issues/problems in the past
D. Project background
E. Specification of the design task
F. Legislation and official regulation
G. Relevant patents, standards and technologies
H. Administrative process of the project
I. Budget and resources
J. Requirement for design & manufacture a product/part
K. What issues to consider and when to consider them
L. Information on material selection and manufacturing methods
M. Others ___________

**5. Please choose three from the options in Question 4 which you think are most important and rank them in descending order in terms of importance**

_____ > _____ > _____

**6. What type of information do you deal with in design tasks _____**

A. Sketch
B. Engineering drawing
C. Calculation and analysis
D. Report/document
E. 3D model
F. Logbook
G. Meeting note
H. Completed forms
I. Figures and tables
J. Pictures
K. Others ___________

**7. How do you generally fulfil your information needs _____ (Please try your best to give the estimated percentage of using a specific method in the brackets after options)**

A. Ask other team members (   %)
B. Refer to documents in the previous projects (   %)
C. Search on the Internet (   %)
D. Search from text books, paper (   %)
E. Read relevant standards (   %)
F. Find through information systems (   %)
G. Others ___________

**8. Please choose the ways you use for sharing information _____**

A. Network drive ( e.g. Google drive, Drop box)
B. Shared folder in the local network (e.g. documents on K drive)
C. Social network (e.g. Facebook)
D. Email
E. Information systems
F. Others software/tools ___________

**9. How do you manage information when you are doing designs _____**

A. Maintain a logbook
B. Store information in working files
C. Store information in electronic documents on a computer
D. Remind information in your brain
E. Using information management software
F. Others ___________

**10. Do you think an information system is useful for the Formula Student project _____**

A. Yes
B. No

**11. What functionalities do you think are useful if an information system is to be developed for information & knowledge management for the Formula Student Project _____**

A. Document management
B. Information retrieval
C. Cooperative work
D. Information visualisation
E. Use of multimedia to show/explain information
F. Intelligent recommendation
G. Support for the design process
H. Providing easy input of design information based on a multilevel knowledge model
I. Others ___________

---

**12. Please choose three from the options in Question 11 which you think are most important and rank them in descending order in terms of importance**

_____ > _____ > _____

---

**13. What kinds of design information do you think will be useful for its effective understanding and reuse in new design projects _____**

A. Design scheme
B. Engineering drawing
C. Design rationale
D. Testing and experiment results
E. Machining and manufacture methods
F. Material selection strategies
G. Contacts (suppliers, manufactures etc.)
H. Project procedure
I. Others __________

---

**14. Please choose three from the options in Question 13 which you think are most important and rank them in descending order in terms of importance**

_____ > _____ > _____

---

**15. What kinds of knowledge do you think is the most useful for effective understanding and reuse _____**

A. What is the issue
B. How to solve the issue
C. Why to solve the issue in this way

# Appendix C

# Research Ethics Review Checklist

# FORM UPR16

**Research Ethics Review Checklist**

**Please include this completed form as an appendix to your thesis (see the Postgraduate Research Student Handbook for more information**

University of Portsmouth

| **Postgraduate Research Student (PGRS) Information** | | | **Student ID:** | UP673385 |
|---|---|---|---|---|
| **PGRS Name:** | Hao Qin | | | |
| **Department:** | School of Engineering | **First Supervisor:** | Hongwei Wang | |
| **Start Date:** (or progression date for Prof Doc students) | | **10/2012** | | |

| **Study Mode and Route:** | Part-time ☐ | MPhil ☐ | MD ☐ |
|---|---|---|---|
| | Full-time ☒ | PhD ☒ | Professional Doctorate ☐ |

| **Title of Thesis:** | Design Knowledge Capture and Reuse in an Integrated and Collaborative Working Environment |
|---|---|
| **Thesis Word Count:** (excluding ancillary data) | 44502 |

If you are unsure about any of the following, please contact the local representative on your Faculty Ethics Committee for advice. Please note that it is your responsibility to follow the University's Ethics Policy and any relevant University, academic or professional guidelines in the conduct of your study

Although the Ethics Committee may have given your study a favourable opinion, the final responsibility for the ethical conduct of this work lies with the researcher(s).

**UKRIO Finished Research Checklist:**
(If you would like to know more about the checklist, please see your Faculty or Departmental Ethics Committee rep or see the online version of the full checklist at: http://www.ukrio.org/what-we-do/code-of-practice-for-research/)

| | |
|---|---|
| a) Have all of your research and findings been reported accurately, honestly and within a reasonable time frame? | YES ☒ NO ☐ |
| b) Have all contributions to knowledge been acknowledged? | YES ☒ NO ☐ |
| c) Have you complied with all agreements relating to intellectual property, publication and authorship? | YES ☒ NO ☐ |
| d) Has your research data been retained in a secure and accessible form and will it remain so for the required duration? | YES ☒ NO ☐ |
| e) Does your research comply with all legal, ethical, and contractual requirements? | YES ☒ NO ☐ |

**Candidate Statement:**

I have considered the ethical dimensions of the above named research project, and have successfully obtained the necessary ethical approval(s)

| **Ethical review number(s) from Faculty Ethics Committee (or from NRES/SCREC):** | 4F9635BDE104834F7E690 1FD2742EC8F |
|---|---|

If you have *not* submitted your work for ethical review, and/or you have answered 'No' to one or more of questions a) to e), please explain below why this is so:

| Signed *(PGRS)*: | Hao Qin | Date: 17/12/2015 |
| --- | --- | --- |